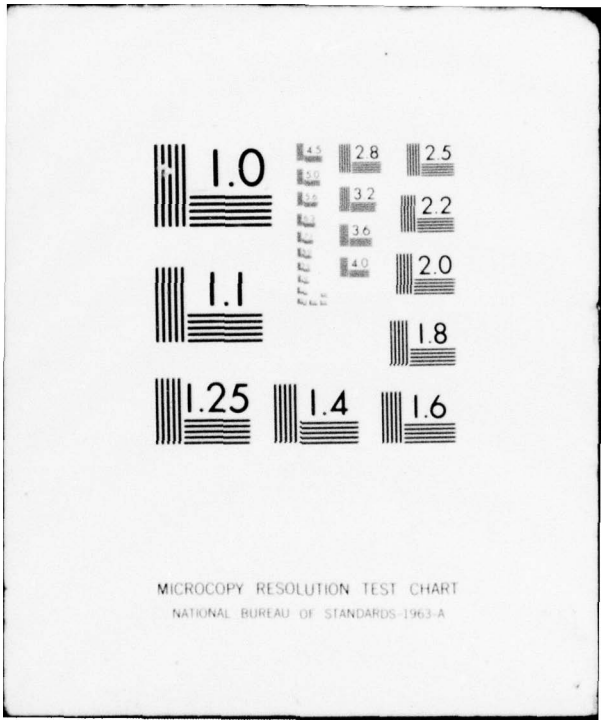
AD-A049 927 MASSACHUSETTS INST OF TECH CAMBRIDGE DEPT OF MECHANI--ETC F/G 13/9
STUDY OF SURFACE FATIGUE WEAR BY EXOELECTRON EMISSION.(U)
DEC 77 E RABINOWICZ, D M BOYD DAHC04-74-C-0028
UNCLASSIFIED ARO-11889.2-E NL

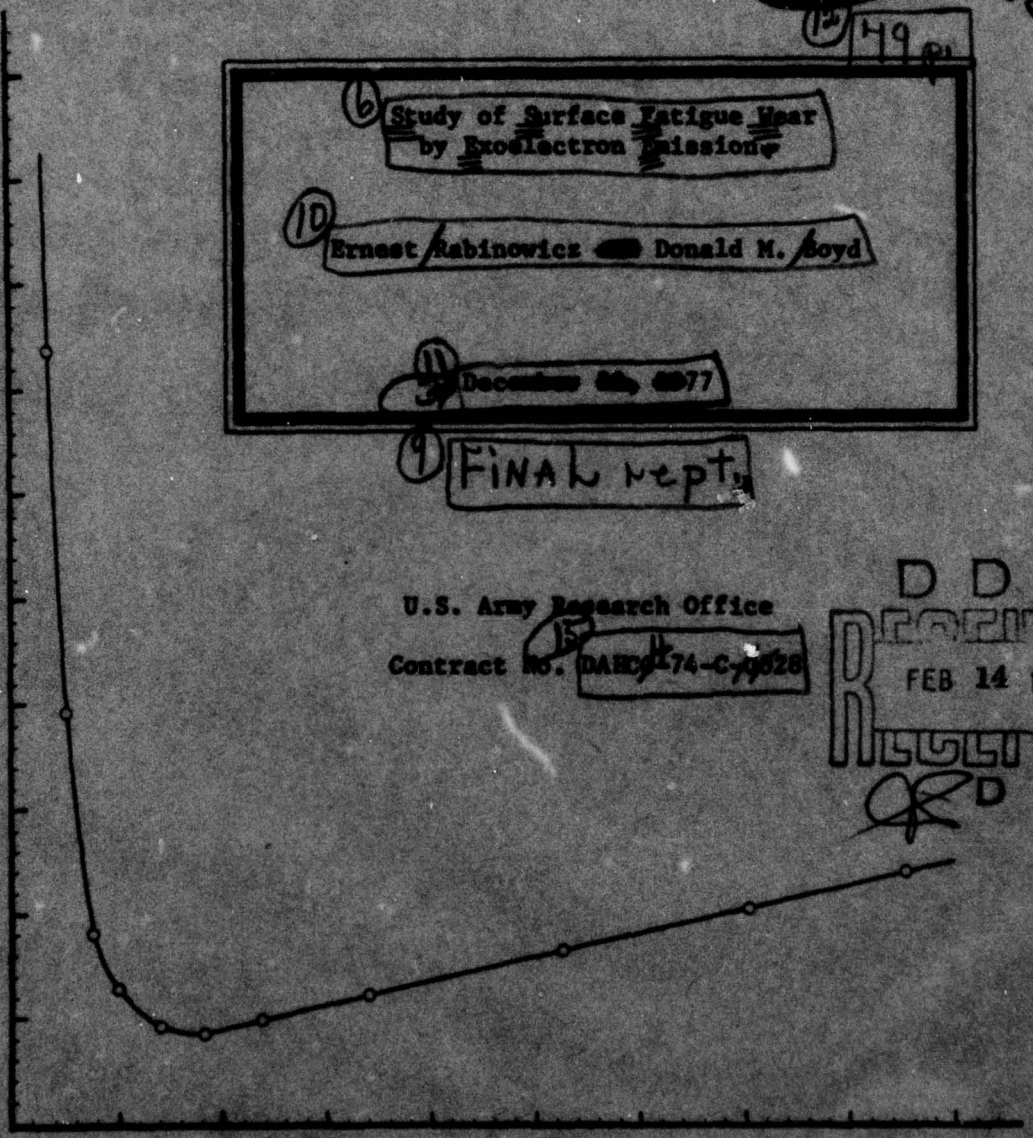
| OF |
AD
A049927

END
DATE FILMED
3-78
DDC


1.0
1.1
1.25
1.4
1.6
2.8
2.5
3.2
2.2
3.6
2.0
4.0
1.8
MICROCOPY RESOLUTION TEST CHART
NATIONAL BUREAU OF STANDARDS-1963-A

ARO 11889.2-E

RESEARCH REPORT



Study of Surface Fatigue Wear by Exoelectron Emission

Ernest Rabinowicz and Donald M. Boyd

December 15th 1977

Final Rept.

U.S. Army Research Office

Contract No. DAHC04-74-C-0028

SURFACE LABORATORY
DEPARTMENT OF MECHANICAL ENGINEERING
MASSACHUSETTS INSTITUTE OF TECHNOLOGY
CAMBRIDGE, MASSACHUSETTS

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) STUDY OF SURFACE FATIGUE WEAR BY EXOELECTRON EMISSION		5. TYPE OF REPORT & PERIOD COVERED Final report 6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Ernest Rabinowicz		8. CONTRACT OR GRANT NUMBER(s) DAHC04-74-C-0028 new
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Mechanical Engineering Massachusetts Institute of Technology Cambridge, MA 02139		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army Research Office Box 12211 Research Triangle Park, NC 27709		12. REPORT DATE December 30, 1977 13. NUMBER OF PAGES 71
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE NA

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

NA

18. SUPPLEMENTARY NOTES

The findings in this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Exoelectrons, Non-destructive testing, Surface fatigue wear, Fatigue, Lubricants

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

An investigation of surface fatigue wear of bearing balls was carried out, using exoelectrons to monitor crack growth prior to spalling. The balls were run in a Barwell 4-ball surface fatigue wear tester, and periodically removed from the tester, cleaned to remove their oil film, transferred to a special vacuum chamber, and illuminated with ultraviolet light. The emitted exoelectrons originating at new surface area generated during fatigue testing were detected by an electron multiplier. By rotating the ball and measuring the exo-

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. Abstract continued

electron emission as a function of position, the sources of the emission could be localized to within the resolution of the scanning spot, 0.08 mm.

Spalling generally occurred at locations where high exoelectron emission had previously been noted, indicating the presence of a growing crack. A more detailed analysis showed that the crack site later became the leading edge of the spall. Fluctuation in the measured intensity of the exoelectrons were traced to the influence of the hot lubricating oil, which reduces the ability of a steel surface to emit exoelectrons, the activation energy of the process being about 0.25 ev, and the half life at an oil temperature of 100°C being about 18 secs.

Study of surface fatigue wear by exoelectron emission

Final report

Ernest Rabinowicz and Donald M. Boyd

December 30, 1977

U.S. Army Research Office

Contract No. DAHC04-74-C-0028

Department of Mechanical Engineering
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

Approved for Public Release;
Distribution Unlimited.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Abstract

An investigation of surface fatigue wear of bearing balls was carried out, using exoelectrons to monitor crack growth prior to spalling. The balls were run in a Barwell 4-ball surface fatigue wear tester, and periodically removed from the tester, cleaned to remove their oil film, transferred to a special vacuum chamber, and illuminated with ultraviolet light. The emitted exoelectrons originating at new surface area generated during fatigue testing were detected by an electron multiplier. By rotating the ball and measuring the exoelectron emission as a function of position, the sources of the emission could be localized to within the resolution of the scanning spot, 0.08 mm.

Spalling generally occurred at locations where high exoelectron emission had previously been noted, indicating the presence of a growing crack. A more detailed analysis showed that the crack site later became the leading edge of the spall. Fluctuation in the measured intensity of the exoelectrons were traced to the influence of the hot lubricating oil, which reduces the ability of a steel surface to emit exoelectrons, the activation energy of the process being about 0.25 ev, and the half life at an oil temperature of 100°C being about 18 secs.

I. INTRODUCTION

The aim of this study has been to use the phenomenon of exoelectron emission to study the process of surface fatigue wear. The research was carried out during a period of three years, from July 1, 1974 to June 30, 1977. The work carried out during the first half of this period has already been published, and the two papers are to be found in Appendix I and in Appendix II. The reader is referred to them for accounts of exoelectrons, of surface fatigue wear, and of the interactions between the two phenomena.

The work carried out in the last half of the project has not yet been published, and a rather comprehensive account of it is given here. A more extensive account is contained in the June 1977 M.S. Thesis of Donald M. Boyd, "Effect of lubricant on exoelectron emission during rolling contact fatigue."

During the second half of the project, an effort was made to improve the reliability and resolution of the exoelectron detection apparatus. Several fatigue tests were then run to obtain exoelectron emission scans (hereafter referred to as EE scans) during the life of the ball bearing. The EE scans were analyzed in several ways. One method of analysis looked at the way in which the EE count varied along the track as an indication of crack movement prior to spall initiation. Also, attempts were made to relate the site of peak EE to the first spall site.

The results of the fatigue tests showed indifferent correlation between EE and the rolling fatigue process. The prefailure scans did not always show a peak at the first spall location. However, the difference in the EE count between the leading and trailing edge of the spall was shown to indicate the direction of the crack propagation.

It was assumed that the presence of the lubricant during the fatigue

tests were influencing the EE count. Accordingly three different lubricants were evaluated to determine their effect on EE, and activation energy and EE half life calculations were made from the lubricant tests. The results of these tests provided new understanding of the events occurring during lubricated rolling contact fatigue tests.

Two research assistants worked on the project, namely Patrick A. March and Donald M. Boyd. They were awarded M.S. degrees in Mechanical Engineering from M.I.T. in June 1975 and June 1977 respectively.

II. THEORY

The theory or theories of the exoelectron emission process will not be repeated here, as they are discussed in Appendix I. However, something should be stated here about activation energy and its application to exoelectron decay rates, since this concept is made much use of later.

The application of the concept of activation energy in the analysis of exoelectron decay rates apparently originated with Pimbley and Francis [1], who attributed the activation energy they calculated, namely .24 eV, to the diffusion of vacancies. Activation energies have also been interpreted as the initial stages of oxidation, and as chemiemission [2].

Calculation of the activation energy is related to the decay of EE. The decay function found to apply to EE is:

$$N = N_o \exp(-\lambda t) \qquad (1)$$

where N = exoelectron count
N_o = constant
λ = rate constant
t = time

EE also follows the Arrhenius equation:

$$\lambda = F_o \exp\left(-\frac{E}{R\theta}\right) \qquad (2)$$

where λ = rate constant from (1)
F_o = constant
E = activation energy
R = universal gas constant (1.978 cal/mole deg)
θ = temperature (°K)

By taking the natural logarithm of equation 1 the rate constant becomes

$$\lambda = \frac{\ln\left(\frac{N_o}{N}\right)}{t} \qquad (3)$$

Combining equations 2 and 3 and taking the natural logarithm the final equation becomes:

$$\ln \ln \left(\frac{N_o}{N} \right) = - \frac{E}{R\theta} + C \qquad (4)$$

where the constant $C = \ln F_o + \ln t$

The activation energy is calculated by plotting $\ln \ln \left(\frac{N_o}{N} \right)$ versus 1/temperature (θ), in which case the slope is equivalent to -E/R.

The activation energies calculated from EE decay studies range from .24 to 1.14 eV [1, 2]. This large variation is not fully understood.

III. APPARATUS

3.1 Introductory Remarks

The research apparatus used in this study was that described in Appendix I. The subsystems of the apparatus include the fatigue wear apparatus, the exoelectron emission detection system, and the specimen positioning system. The fatigue tester is a standard Barwell four ball tester with a gravity feed lubrication system. The exoelectron detection system uses a focused ultraviolet light spot to stimulate the emission of the exoelectrons (see figure 1). Electrons are detected by a Channeltron Electron Multiplier and counted by a Baird Atomic Scaler rate meter. The output from the ratemeter is displayed on the Y-axis of a Mosley X-Y recorder. A ferrofluidic rotary vacuum feedthrough, coupled to a digitally controlled stepping motor controls the specimen positioning. The rotary feedthrough is positioned at the starting point and the signal corresponding to the rotational position is read on the X axis of the X-Y recorder. The output obtained from a test is a plot of electron counting rate vs. rotational position. Various design changes were made to the system in order to improve the reliability of EE scans.

Changes to the system subsequent to the tests described in Appendix I can be grouped into four areas: electronic, vacuum, optical and specimen positioning.

3.2 Electronic System Improvement

The electrical changes made to the system were implemented to improve the signal-to-noise ratio by lowering the background counting

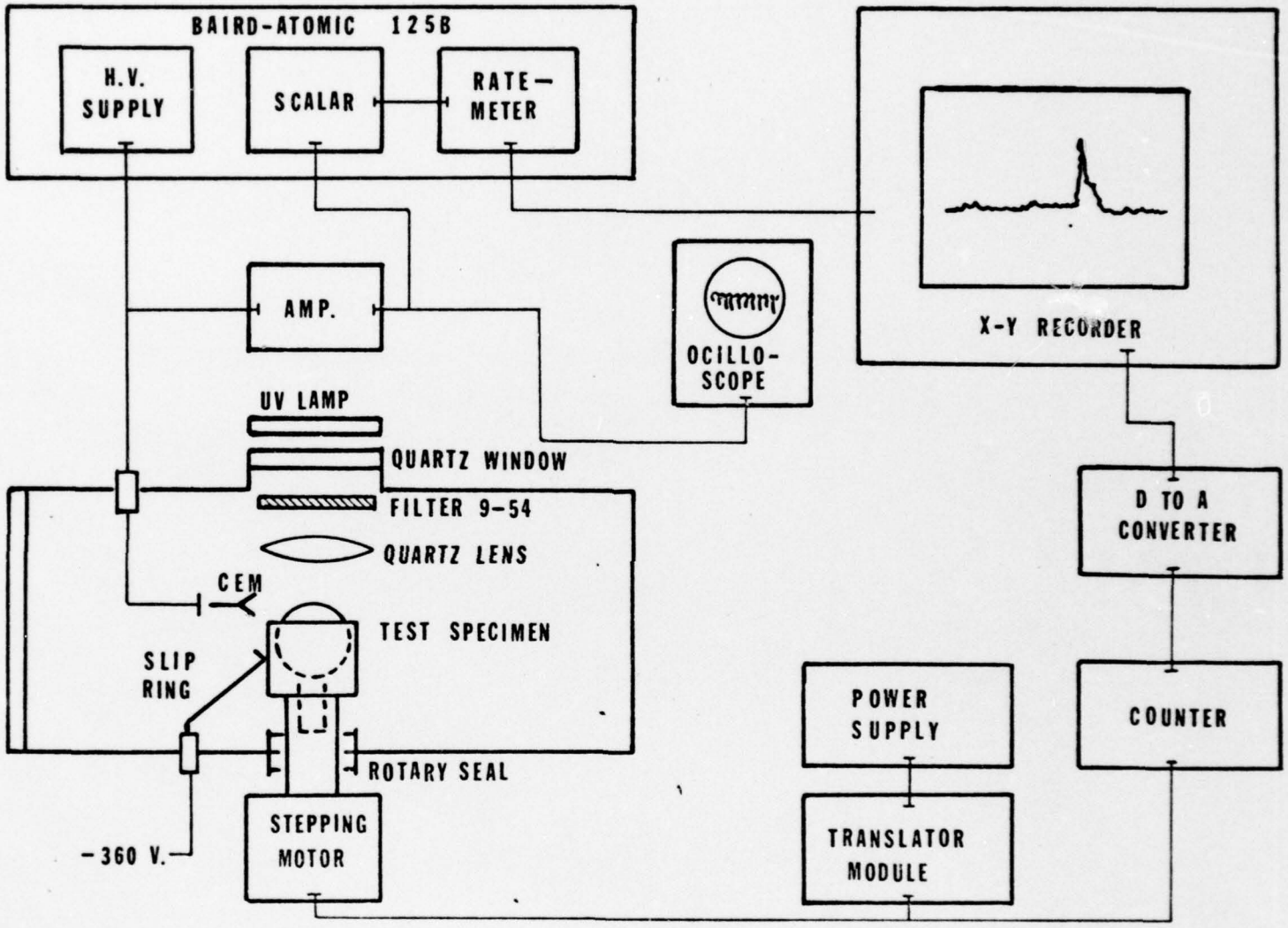


Figure 1 - Research apparatus for stimulating and detecting exoelectron emission.

rate of the Channeltron electron multiplier. This was accomplished by changing all unshielded wires leading from the electron multiplier to the Baird Atomic scaler ratemeter, to shielded cables. The preamplifier circuit was also placed in a container for both shielding and safety reasons.

3.3 Vacuum System Improvement

The efficiency of the vacuum's system was improved by the use of a liquid nitrogen cold trap. The previous tests run in this vacuum system used only the roughing pump and obtained a pressure of 7×10^{-4} torr. Without the use of a cold trap, the backstreaming of the oil from the roughing pump caused the electron multiplier to decrease its sensitivity and, as a result, had to be replaced. A second effect on the electron multiplier at this pressure was that the detector was at its lowest limit of responsiveness. In order to use the mercury diffusion pump, and a liquid nitrogen cold trap, a vent valve was placed in the detection chamber. By closing off the detection chamber from the rest of the system, it could be vented to atmosphere while the diffusion pump and the roughing pump remained functioning. With this system, the total pumping time was reduced by three minutes and a final pressure of 5×10^{-5} torr was obtained. This system prevented backstreaming of oil from the roughing pump and provided a vacuum within optimal range for the electron multiplier.

3.4 Optical System Improvement

The function of the optical system is to focus a spot of ultraviolet light onto the wear track of a ball bearing. This is accomplished by passing the ultraviolet light through a slit to a lens which focuses the light on the ball bearing. The resolution of the system is a function of the width of the focused UV spot. Earlier tests used a .27 mm spot. In order to improve the resolution, an adjustable slit device was designed and set for a spot width of .08 mm. for the majority of the fatigue tests. The spot width was set at .03 mm for the tests investigating the effect of a lubricant on EE.

An ultraviolet light filter was added to the system to reduce the background counting rate. The filter chosen is described in the filter tests results, chapter four. The filter was placed between the UV light and the quartz lens (see figure 1).

3.5 Specimen Positioning Improvement

A new ball holding fixture was designed to improve the realignment accuracy between the Barwell four ball fatigue tester and the exoelectron apparatus. Earlier tests required the grinding of a flat surface on the half inch ball to which a .25 inch positioning rod was epoxied. The main problem encountered with this technique was that the ball and rod frequently broke apart and alignment accuracy was lost. The new holding fixture required no machining of the ball bearing. The ball bearing is held tightly in position by a holding cap, (see figure 2). The repositioning accuracy was obtained by using a set screw against a milled flat and is repeatable to better than 0.5

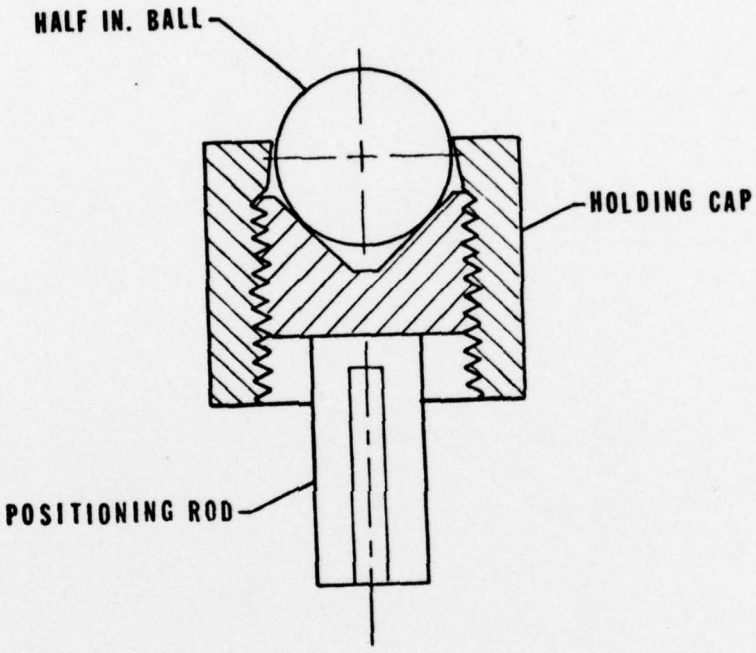


Figure 2 - Cross sectional view of bearing ball holding and positioning fixture. Scale 2:1.

degrees of rotation. The ball holding fixture is held in place with a set screw when running in the Barwell four ball tester.

IV. RESULTS

A. FILTER TESTS

4.1 Introduction

Photostimulated exoelectron emission is similar to the photoelectric effect in that both forms of emission are related to the work function of the electron. Since the electrons emitted by the photoelectric effect add to the background counting rate, it would be beneficial to use wavelengths that inhibit the photoelectric effect and stimulate EE. Most metals have a workfunction of 3 to 3.5 eV, [3]. Exoelectrons have a lower energy requirement as a result of deformation to the metal surface.

The emission from the ultraviolet (UV) light source used in the research apparatus is from a low pressure mercury discharge. The equivalent energies of the six major emission lines of the source can be calculated by the equation

$$\phi = \frac{1.24 \times 10^4}{\lambda(\text{Å})} \qquad (5)$$

ϕ = electron workfunction

λ = wavelength

λ(Å)	ϕ(eV)
2537	4.88
3125	3.97
3650	3.39
4047	3.06
4388	2.84
5461	2.23

Three ultraviolet light filters were tested in order to lower the background counting rate without affecting the EE rate. Filters BG-13, LG-100-2 and 9-54 stop wavelengths shorter than 4047Å, 3650Å and 3125

respectively.

4.2 Procedure

A 52100 ball bearing was cleaned in a Freon degreaser. A scratch was put on the ball with a diamond scriber across the scanning spot and the ball was placed in the vacuum chamber. Exoelectron scans were taken without a filter as a control. The chamber was then opened and a filter was placed above the quartz lens. Filtered scans were then made. The chamber was again opened, the filter was removed and another scan was taken to ensure that no appreciable exoelectron reduction had occurred. This procedure was used for all three filters.

4.3 Results

Figure 3 shows the exoelectron emission scan control results for tests using filters BG-13 and LG-100-2. Figure 4 shows the scan obtained when filter BG-13 was used. Figure 5 shows the scan obtained when filter LG-100-2 was used. The final scan taken without the filters showed no change in emission rate from figure 3.

Figure 6 shows the control scan, and figure 7 shows the filtered scan used with filter 9-54.

4.4 Conclusion

In order to evaluate the filters, a signal-to-noise factor was computed using the formula:

$$\frac{\text{Exoelectron Peak - Background}}{\text{Exoelectron Peak}}$$

The optimum value for this ratio is one. The ratio was calculated for each scan. The average ratio for the control scans was .74. The

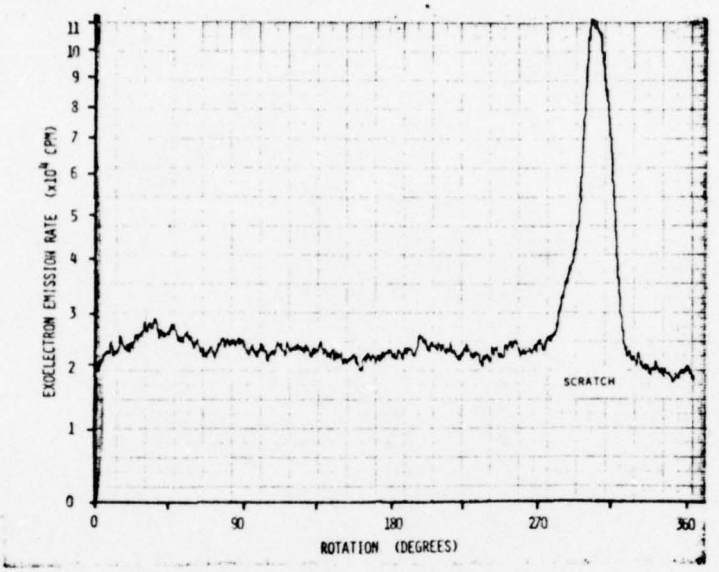


Figure 3 - EE from scratched ball used as a control scan for filters BG-13 and LG-100-2.

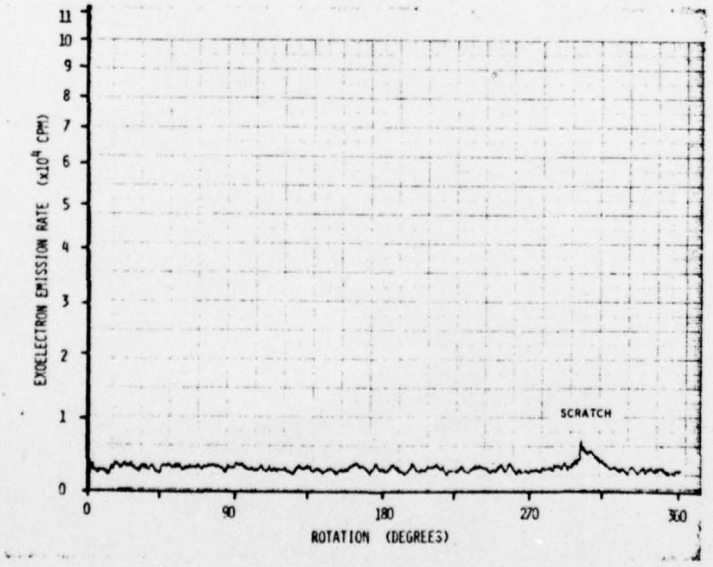


Figure 4 - EE from scratched ball using ultraviolet light filter BG-13.

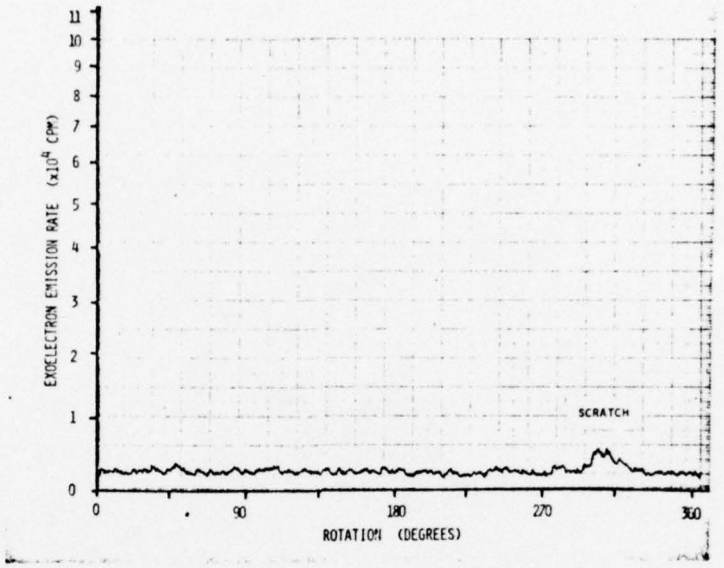


Figure 5 - EE from scratched ball using ultraviolet light filter LG-100-2.

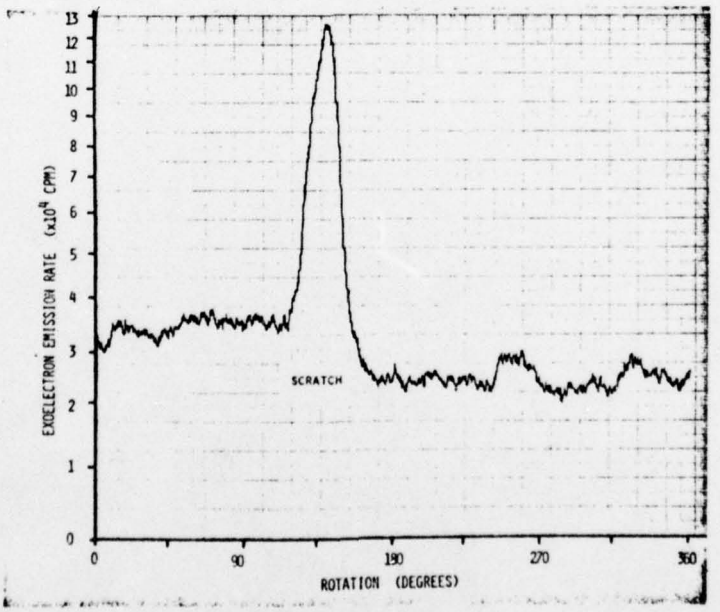


Figure 6 - EE from scratched ball used as a control scan for ultraviolet light filter 9-54.

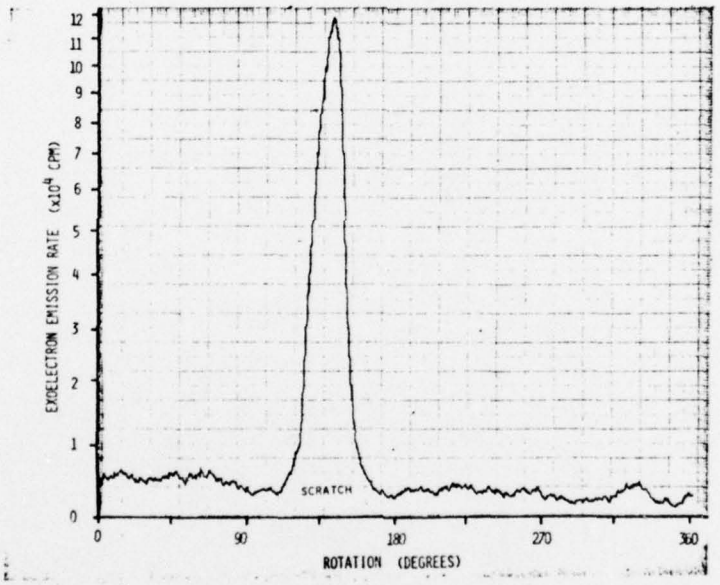


Figure 7 - EE from scratched ball using ultraviolet light filter 9-54.

ratio for the filter BG-13 was .58. The ratio for the filter LG-100-2 was .50. The filter 9-54 had a ratio of .97.

The results of the test showed that filter 9-54 had a 23% increase in efficiency over the control scan. Filters BG-13 and LG-100-2 showed a decrease in efficiency. Filter 9-54 was chosen for the use in all future tests because it significantly increased the sensitivity of the exoelectron detection apparatus. This filter has been used by Baxter [4], for his EE research.

V. RESULTS

B. FATIGUE TESTS

5.1 Introduction

The results of the earlier fatigue tests showed that EE could locate the position of the eventual fatigue spall [5]. These first tests were run in a Barwell tester at a load of 800 lbf and a typical failure time was 34 minutes. Although the results looked promising, additional testing was required to determine the limits of the EE technique. A research program was begun in which longer life fatigue tests were used as a method of determining the correlation between EE and the fatigue process.

Fatigue tests of longer duration are necessary for two reasons. The first is related to the utilization of lighter loads in the four ball tester to obtain longer life tests. Lighter loads are important because it has been found that heavy load tests are not indicative of real life bearings situations [6]. The closer the fatigue test conditions are to normal bearing situations the more useful the EE fatigue monitoring technique will be. The second reason for the longer life fatigue tests is to allow for a greater number of EE scans to be made prior to the bearing ball failure.

The objective of the test program is to evaluate the prefailure EE scans in terms of the rolling contact fatigue process. EE scans are periodically made during the fatigue test. A final EE scan is made when the first spall occurs on the bearing ball. The prefailure EE scans are examined along the wear track for sites of peak EE.

These sites should indicate the formation of the first spall. Pre-failure EE scans are also examined for comparision of EE and the percent of rolling contact fatigue.

5.2 Procedure

A 52100 ball bearing was placed in the holding fixture and secured by tightening the holding cap. The specimen was then ultrasonically cleaned in a bath of Freon TF degreaser and placed in the exoelectron scanning apparatus. An initial scan was then made. The ball was then placed in the Barwell four ball tester. The lower three balls of the tester were also 52100. A low volatility diester based synthetic oil [7], Shell Turbo TJ-15, was used for all tests. Four tests each at loads of 400, 660, and 824 pounds were run. At various intervals during the test the Barwell tester was stopped, the specimen cleaned, and an exoelectron scan of the wear track was made.

During the series of fatigue tests the exoelectron detection apparatus was continuously being improved. The four tests run at a load of 660 pounds were monitored by the exoelectron apparatus using an ultraviolet light spot of 0.27 mm by 2 mm without the filter. The spot width was changed to 0.08 mm for the 824 pound tests. After the filter 9-54 was added to the detection system three tests at a load of 400 pounds were run. The spot width was again changed to 0.03 mm for the final test at 400 pounds.

5.3 Results

The EE scans from each fatigue test were examined for sites of

peak emission indicating the location of the future spall. The first set of four fatigue tests used the same load of 824 lbf as was used in earlier testing. Only two out of the four tests produced prefailure EE scans with emission peaks at the spall site. Figures 8 through 11 show the results of the EE scans made during test 14. In figure 10, peak emission is seen prior to failure at a site which later becomes the spall site.

Each of the four fatigue tests run at a load of 660 lbf showed EE peaks at least once in the prefailure scans at the location of the spall. Depending on the life of the bearing ball, the number of prefailure EE scans ranged between 1 and 11. These prefailure scans did not always show emission peaks at the site of the spall. For example, the EE scans for test 8 are shown in figures 12 through 17. Figures 13 and 14 show peaks at the eventual spall site.

In the four 400 lbf fatigue tests there were EE peaks at the spall site early in the test. However, in two out of the four tests, there was no distinguishable EE peak at the spall site after spalling occurred!

A Weibull plot of each series of tests is shown in Figures 18 to 20.

In 83% of the tests the prefailure EE scans showed a peek at the location of the future spall. However, the EE at the spall site did not always produce the highest emission rate and this was something of a disappointment.

Because our fatigue monitoring technique allows for a quantitative value to be obtained at each location of the bearing ball wear track, the emission data can be utilized in various ways to help determine the nature of the fatigue process. Two methods of using the EE rates at various sites on the fatigue scan were tried. The first method uses a cum-

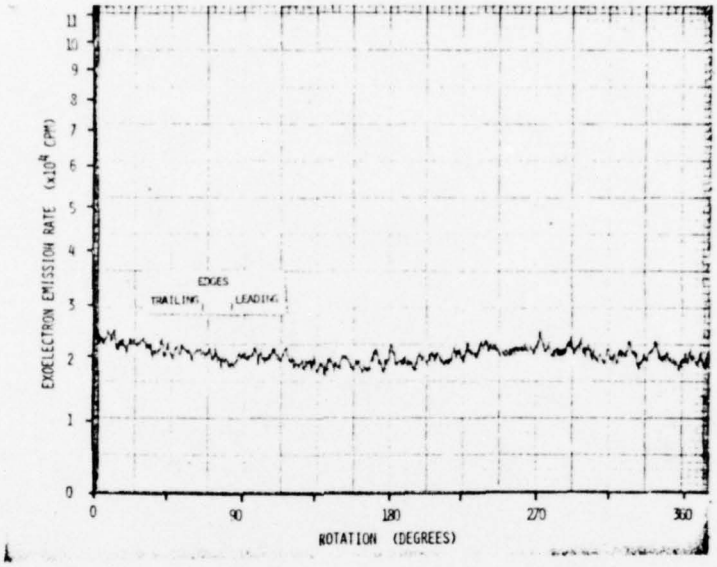


Figure 8 - EE from 52100 test ball before four-ball test at a load of 824 lbf (Test 14).

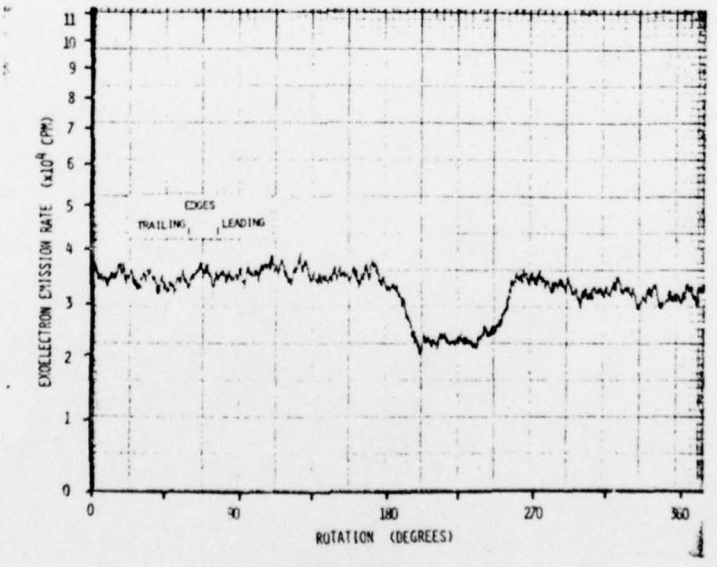


Figure 9 - EE from 52100 test ball after 12 minutes in four-ball tester at a load of 824 lbf (Test 14).

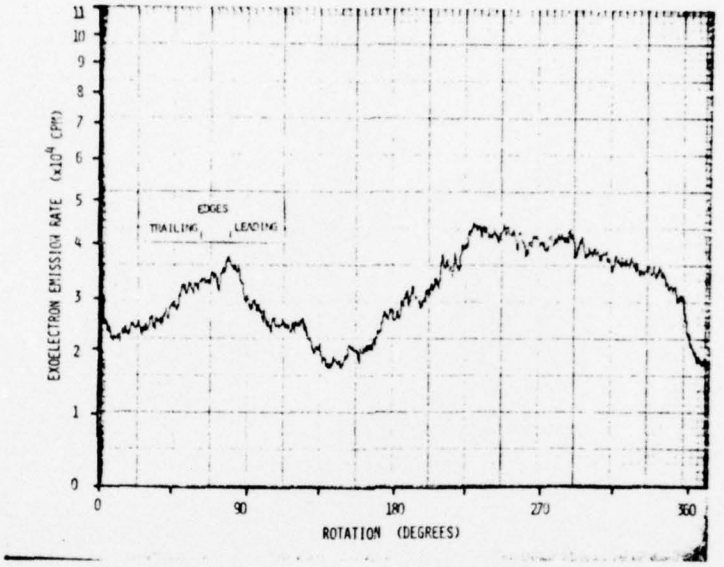


Figure 10 - EE from 52100 test ball after 30 minutes in four-ball tester at a load of 824 lbf (Test 14).

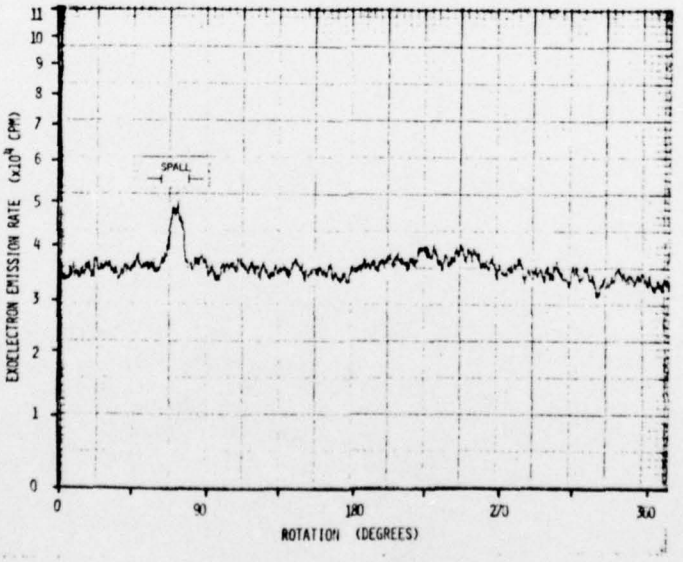


Figure 11 - EE from 52100 test ball following first spall formation after 36 minutes in four-ball tester at a load of 824 lbf (Test 14).

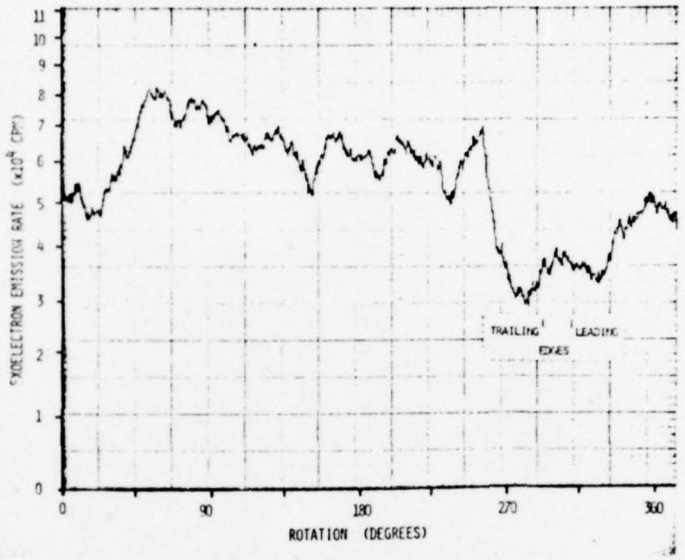


Figure 12 - EE from 52100 test ball before four-ball test at a load of 660 lbf (Test 8).

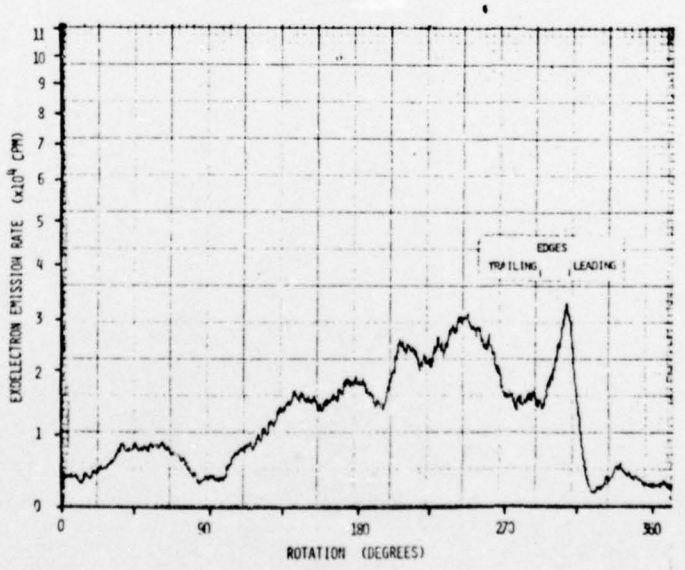


Figure 13 - EE from 52100 test ball after 1.1 hours in four-ball tester at a load of 660 lbf (Test 8).

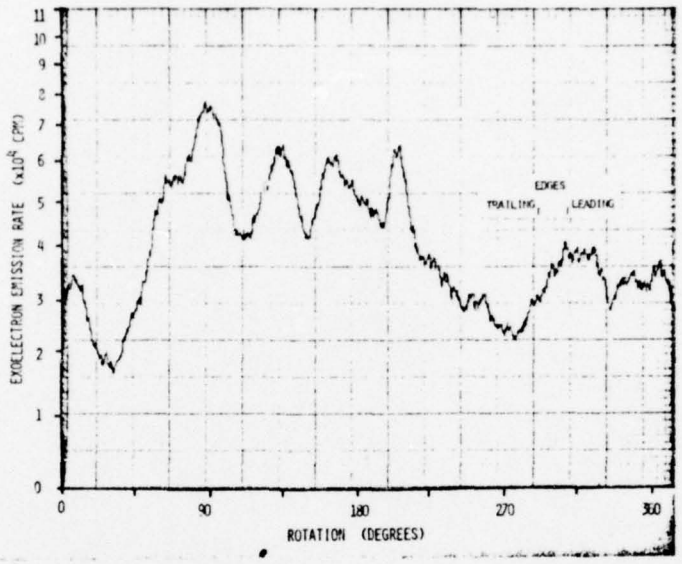


Figure 14 - EE from 52100 test ball after 2.2 hours in four-ball tester at a load of 660 lbf (Test 8).

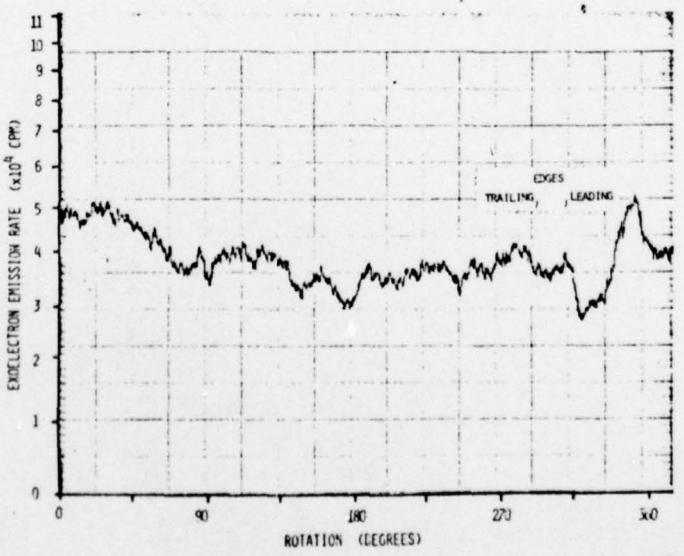


Figure 15 - EE from 52100 test ball after 3.0 hours in four-ball tester at a load of 660 lbf (Test 8).

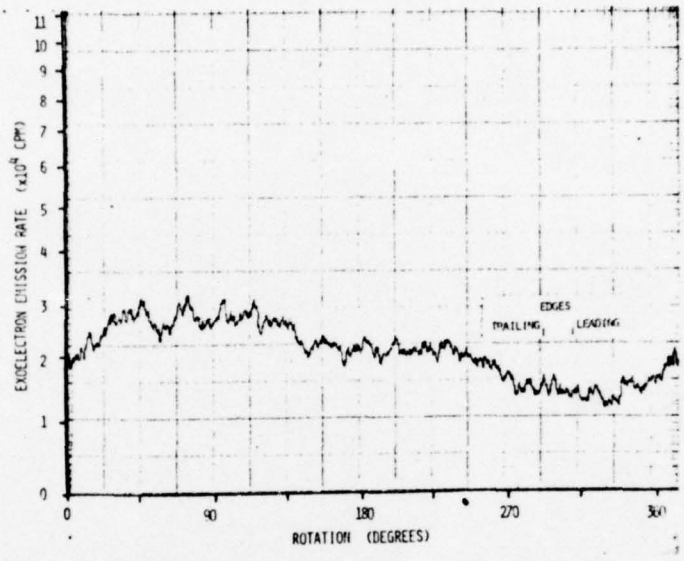


Figure 16 - EE from 52100 test ball after 9.6 hours in four-ball tester at a load of 660 lbf (Test 8).

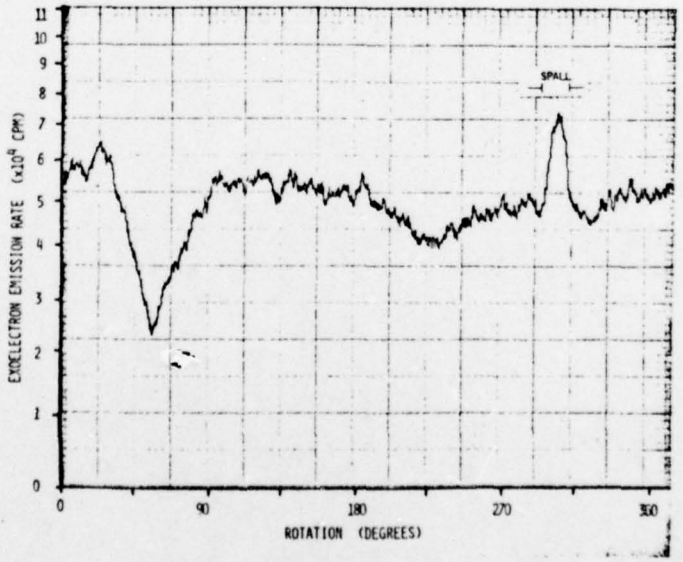


Figure 17 - EE from 52100 test ball following first spall formation after 15.2 hours in four-ball tester at a load of 660 lbf (Test 8).

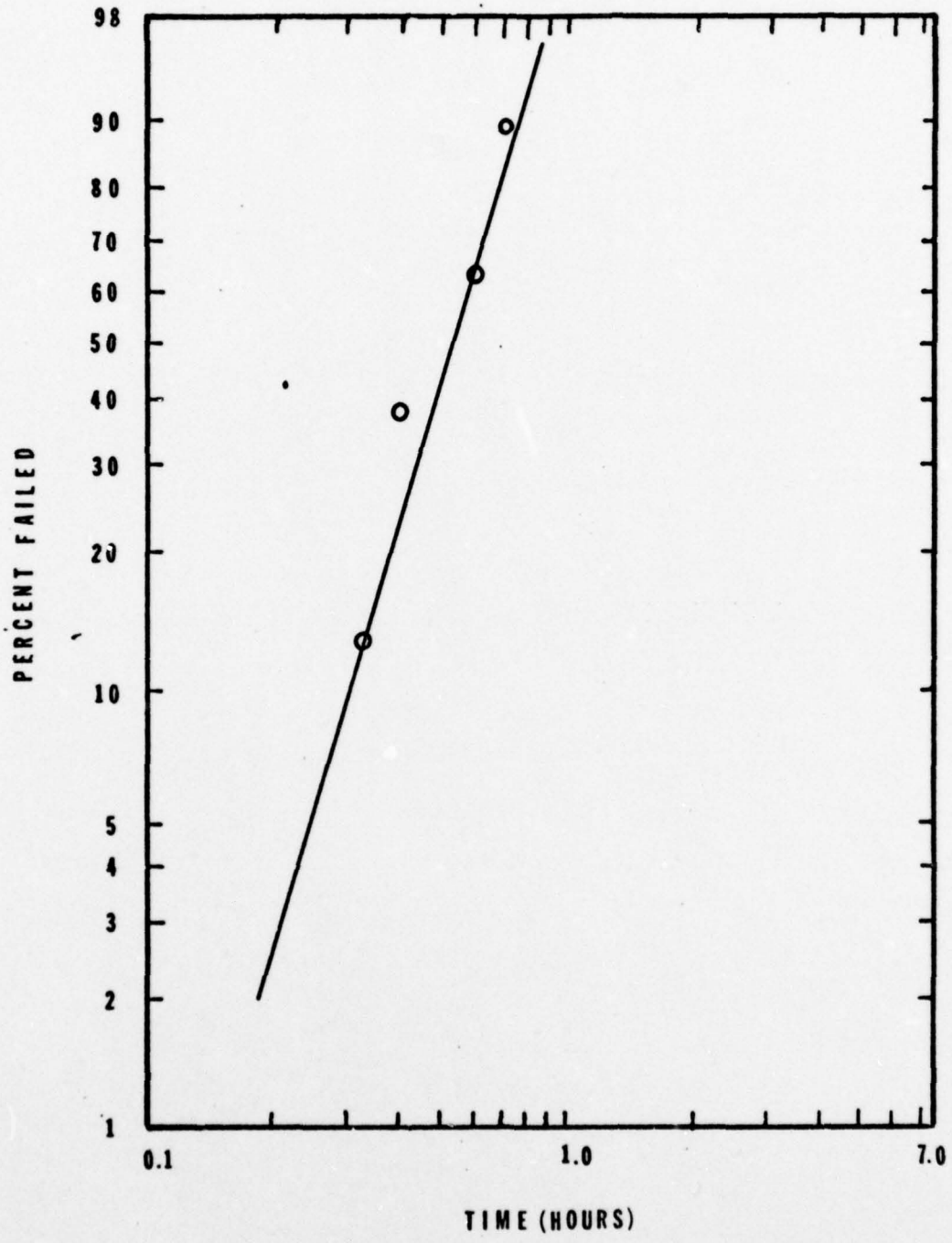


Figure 18: Weibull plot of fatigue test run in Barwell tester at a load of 824 lbf

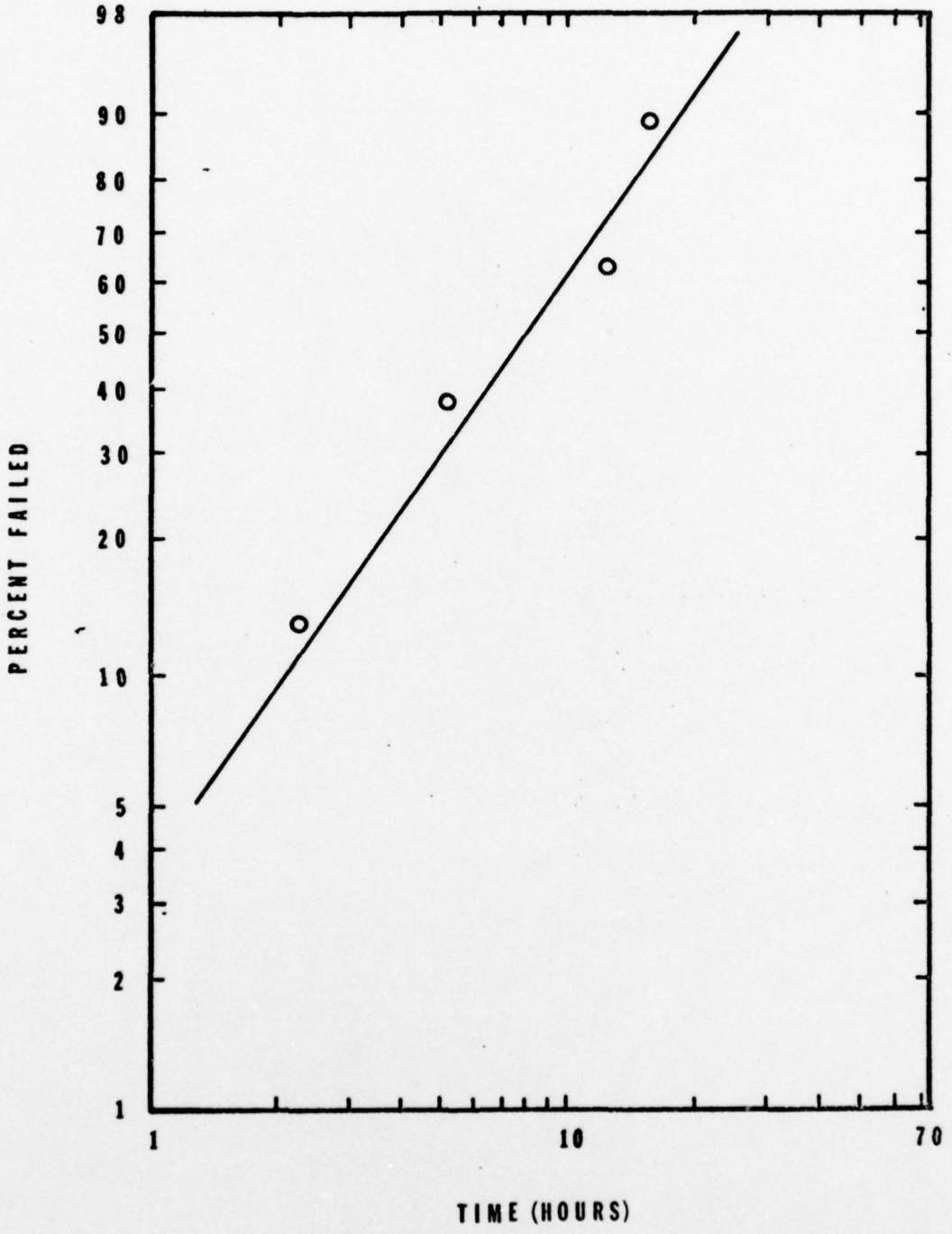


Figure 19: Weibull plot of fatigue test run in Barwell tester at a load of 660 lbf.

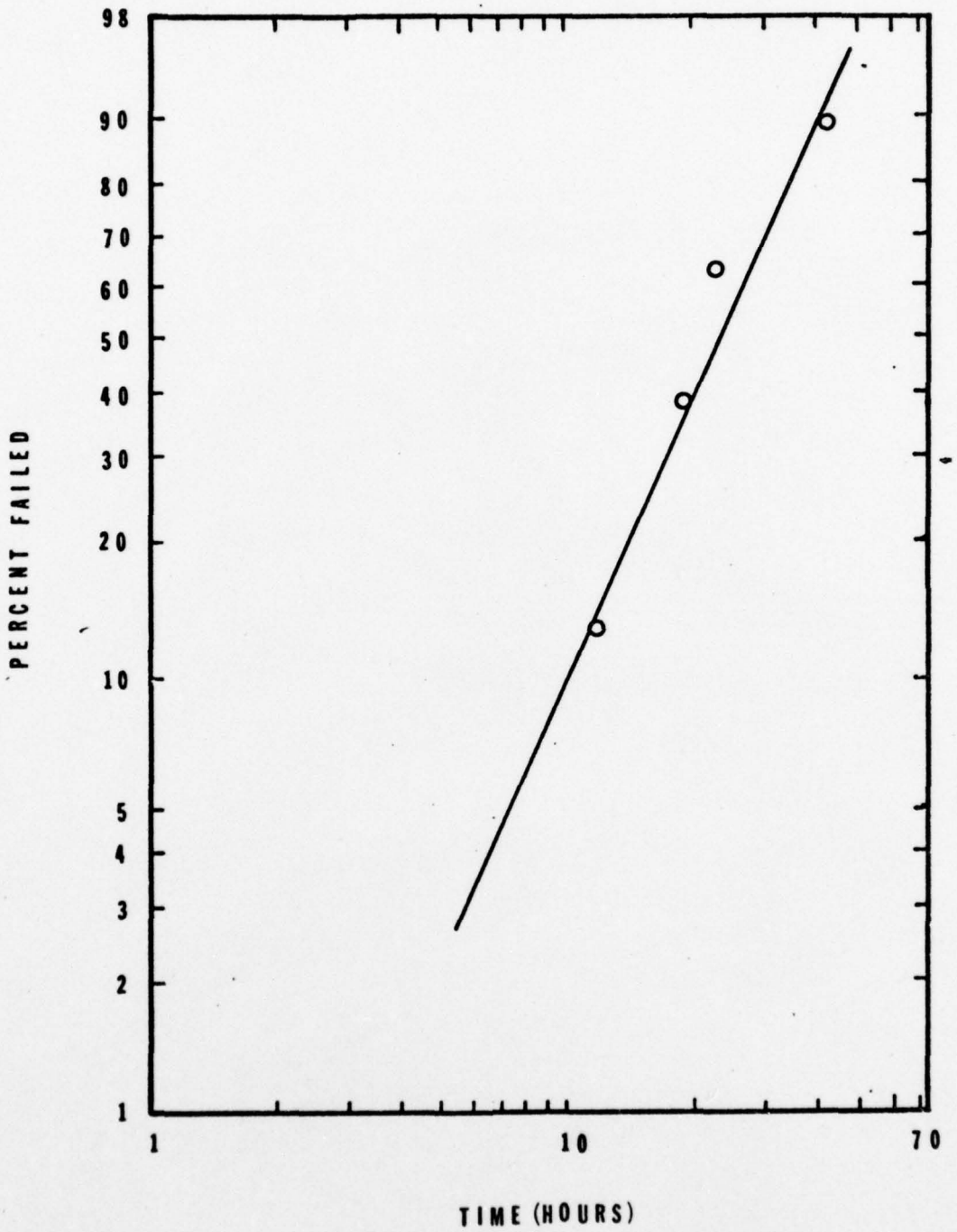


Figure 20: Weibull plot of fatigue test run in Barwell tester at a load of 400 lbf.

ulative technique in an attempt to locate the spall site continuously during the life of the ball.

In the analysis of the exoelectron scans taken over the life of a rolling contact fatigue test, it was found that the site of peak exoelectron emission did not always coincide with the first spall site. It was also known that exoelectron emission decayed in an exponential manner. Therefore if a fatigue crack was initiated from the surface, the exoelectron emission rate would begin to decay. The majority of the exoelectron emission would occur in the area where crack propagation was currently in progress, rather than where the largest total amount of crack propagation had occurred.

Based on these assumptions, a chart was drawn up in which the total amount of the exoelectron emission was successively added for each point of the track in order to plot a time history of the exoelectron emission rate over the life of the ball. The results of the test run at 660 lbs. and failing in 15.2 hours is shown in figure 21.

The results show that the leading edge of the eventual spall had the highest cumulative exoelectron emission site for the first 50% of the life. Thereafter, three regions began to surpass it in total amount of emission.

The second technique compared the prefailure EE rates at the leading and trailing edges of the spall. The leading edge as defined by Syniuta and Corrow [7] is the edge first contacted between the spalled upper ball and a lower ball in the Barwell tester. A relative emission rate was determined for each location by dividing the EE rate at the desired site by the average emission rate of the entire scan. Plots of the relative EE rate versus the life of the bearing ball

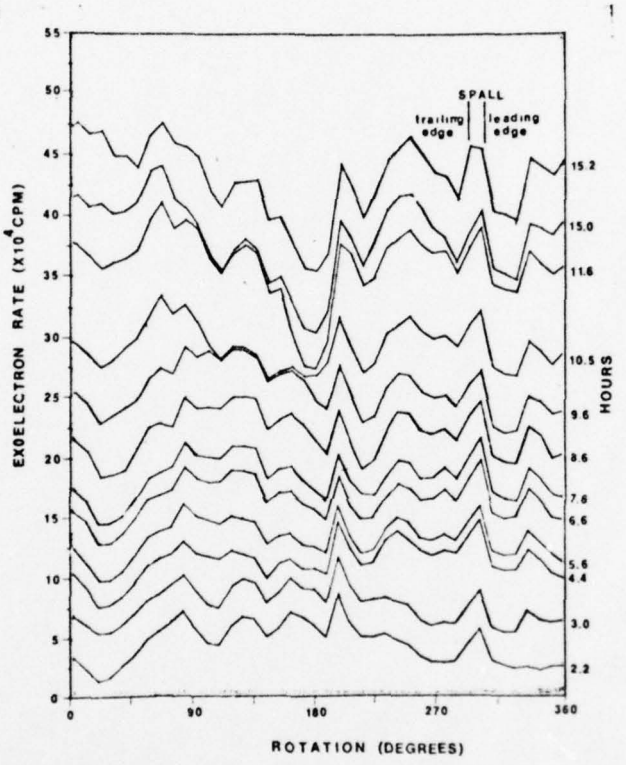


Figure 21 - Cumulative EE count versus specimen position for four ball test at 660 lbf (Test 8).

were made for the leading and trailing edges of the spall. This type of analysis required that several prefailure scans be available and only one spall site be present. An example of using this analysis technique is shown in figure 22. It will be seen that the site of the leading edge of the eventual spall gave an early peak in emission, while the trailing edge gave none. This indicates that spalling is nucleated from the leading edge.

This result corresponds with the fractographic study of rolling contact fatigue by Syniuta and Corrow [7] which states that fatigue failures are initiated in the leading edge area. The majority of the crack propagation in a spall occurs below the surface such that EE could not be detected. This appears to be the best explanation for the lack of prefailure EE peaks at the spall site.

5.4 Discussion

Initial examinations of the EE scans were made with the intent of predicting the spall site. The fatigue tests showed that EE peaks at the spall site in the prefailure scans were not always repeatable occurrences. This could be explained by several different theories. The spall formation could be the result of periods of growth and no-growth of the fatigue cracks. If subsurface cracking were the mode of fatigue spall formation, the exoelectron emission would be unlikely to register crack growth at all. Finally, the technique of EE detection below the surface depends for its effectiveness on the fatigue crack shape. Figure 23 shows two possible cracks, one in which EE detection is possible and one in which it is not possible.

One other explanation for the low EE rate at the spall site is related to the presence of a lubricant during the fatigue test. Several

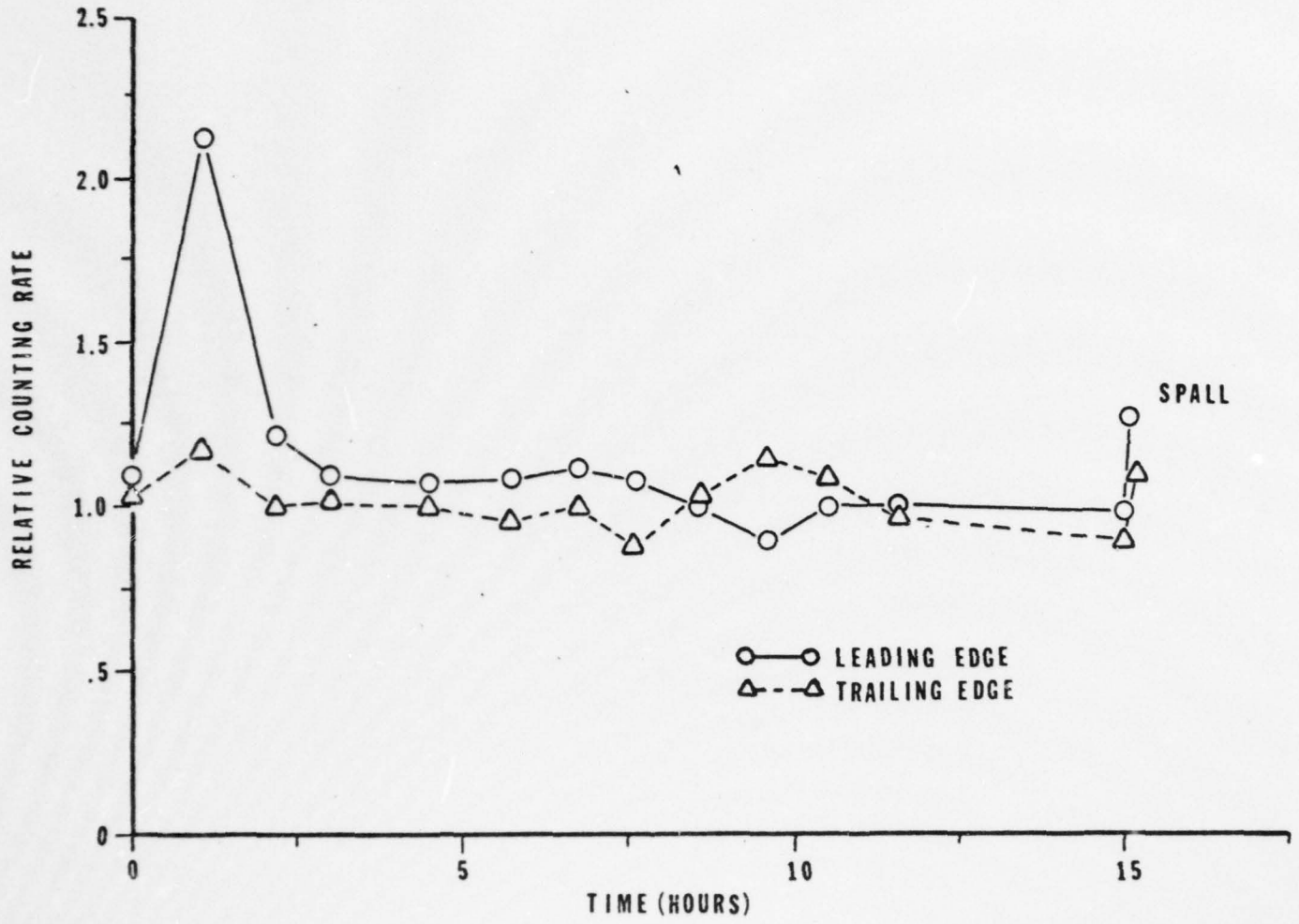


Figure 22 - Relative EE rate versus time of leading and trailing edge of spall from 660 lbf fatigue test (Test 8).

of the final EE scans did not show a large EE peak at the spall. This result indicated that the lubricant could be affecting the EE rate.

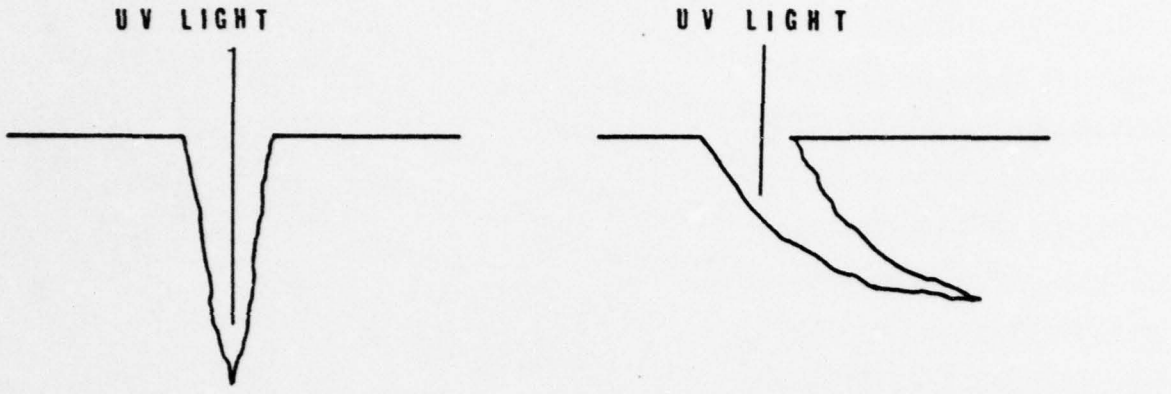


Figure 23 - EE detection from fatigue crack.

VI. RESULTS

C. INFLUENCE OF AIR AND LUBRICANTS ON EXOELECTRON EMISSION

6.1 Introduction

In analyzing the fatigue tests, it became apparent that the lubricant being used was influencing the EE rate. Previous research had shown that EE was affected by oxidation, adhesion, and adsorption [8, 9, 10, 11, 12]. Each of these processes could be present in a metal-lubricant interface. In order to investigate the decay rate of EE and how it is effected by the presence of a lubricant, the fatigue tests were interrupted and a new series of tests were run.

The test program was divided into two areas. First, a comparison of the EE rate in air and in a vacuum was made. The total amount of of EE in counts per square centimeter was calculated from the decay of EE in air and the decay of EE in a vacuum.

The second portion of the test program evaluated the effect of three different lubricants on the EE rate of a 52100 bearing ball scratched in air. The activation energy and the EE half-life were calculated from the results of these tests.

6.2 Comparison of Exoelectron Emission Rate between Air and Vacuum

6.2.1 Procedure: Exoelectron Decay in Air and Vacuum

A half inch 52100 bearing ball was placed in the holding fixture and ultrasonically cleaned in a Freon TF degreaser. Two different sized scratches were put on the ball using a diamond scriber. The bearing ball was immediately placed in the vacuum chamber where EE

scans were periodically made. In tests one and two, the EE rate was allowed to decay in a vacuum of 10^{-4} torr. In test three the ball was taken out of the EE detection chamber between scans and allowed to decay in air.

For these tests there was no ultraviolet light filter and the width of the UV spot was .08 mm.

6.2.2 Results

Figure 24 shows the EE decay curve in a vacuum of 10^{-4} torr. The results of both tests one and two are plotted. The background counting rate was subtracted from the EE peaks found at the two scratches for all tests. Figure 25 shows the EE decay curve in air.

To calculate the counts/cm^2 the total number of exoelectrons emitted was calculated by taking the area under the decay curves and dividing by the ultraviolet light spot size (7.55×10^{-4} cm^2). The results of this calculation are shown in Table 1.

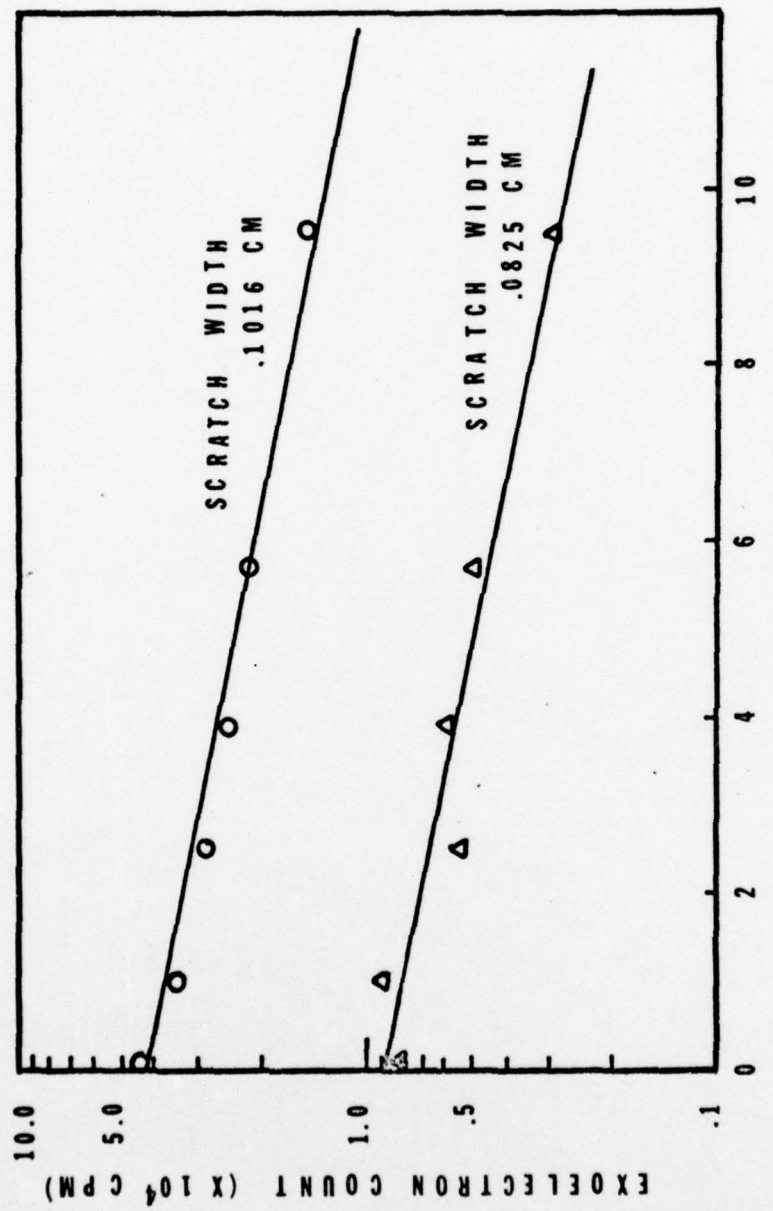


Figure 24 - EE rate versus time of a scratched ball allowed to decay in a vacuum of 10^{-4} torr.

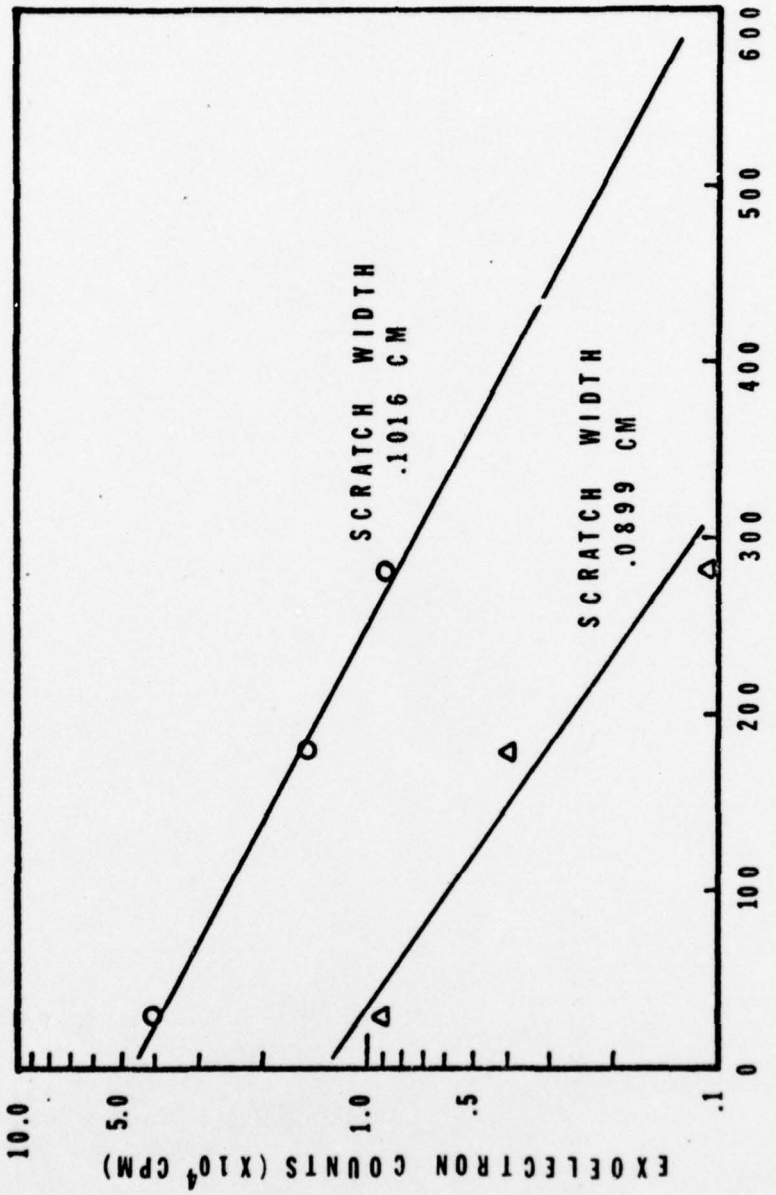


Figure 25- EE rate versus time of a scratched ball allowed to decay in air.

TABLE 1

A. Decay in vacuum

	Width of scratch	TOTAL counts/cm^2 (minus background)
1)	.0825 cm	4.4×10^{12} counts/cm^2
2)	.01016 cm	$.84 \times 10^{12}$ counts/cm^2

B. Decay in air

	Width of scratch	TOTAL counts/cm^2 (minus background)
1)	.0899 cm	9×10^{9} counts/cm^2
2)	.01016 cm	1.47×10^{9} counts/cm^2

6.3 Effect of a Lubricant on Exoelectron Emission

6.3.1 Procedure: Exoelectron Decay in a Lubricant

A series of tests were run in order to evaluate the effect of a lubricant at various temperatures on EE. The testing procedure involves putting a series of scratches on a half inch 52100 steel ball bearing. In order to insure that all the scratches were the same, a mechanical device was built which allowed the scratch to be put on under a known load. A three pound load was used for all tests. Four scratches were placed on each test ball so that an average emission rate could be determined.

For each data point, a ball was scratched and immediately placed in the detection apparatus where several scans were taken. The chamber was then opened and the ball immersed in a lubricant bath at a known temperature. It was then cleaned with a freon degreaser in an ultrasonic cleaner for three minutes. The ball was then placed in the detection apparatus and the exoelectron scans were made.

This procedure was used for three different lubricants, Nujol mineral oil, CAM 2 SAE 30 heavy duty motor oil, and Turbo TJ 15. The following combinations of lubricant, ball bearing material, and immersion time in the lubricant were used:

Lubricant	Material	Immersion Time
Turbo TJ-15	52100 steel	10 sec, 1 min., 5 min.
	aluminum	1 min.
	stainless steel	1 min.
Nujol	52100 steel	1 min., 5 min.
CAM 2	52100 steel	1 min., 5 min.

A test using a brass bearing ball was started but it was found that the location of the scratches during the initial scan were not readily distinguished from the background counting rate.

The temperature of the oil bath was controlled by a microwatt heater and a thermocouple. In order to have a uniform temperature in the bath, an electric stirring arm was used for mixing the oil. The temperature range of the test was from 20°C to 120°C. The exoelectron detection apparatus used the UV light filter, and the UV spot size was .033 mm. wide.

6.3.2 Results

By using equation 4 section 2.4 the activation energy can be calculated. A plot of $\ell n\ \ell n \frac{N_o}{N}$ versus inverse temperature of the lubricant bath gives a slope equal to -E/R. The variables N_o and N are the EE rates at zero time and after immersion time t in the lubricant bath. R is the universal gas constant. Therefore, each variable of equation 4 is known except the activation energy E which can be calculated from the slope. The value of C in equation 4 is not necessary in the activation energy calculation, the results of which are shown in Table II.

In the first calculation of the activation energy, the value of N_o was taken to be the EE peak minus the background obtained prior to immersion in the lubricant bath. However, it was found that when the log of the EE count at the peak was plotted as a function of the lubricant immersion time, the extrapolated value of N_o was not the same EE rate as that measured prior to immersion. Since the extrapolated N_o value gave more consistent results, it was used in our calculations. Figure 2 shows the EE count versus immersion time for a scratched

TABLE 2

Test Condition	Activation Energy (eV)
52100 steel in Turbo TJ-15 for:	
1) 10 seconds	.15
2) 1 minute	.22
3) 5 minutes	.14
52100 steel in Nujal for:	
1) 1 minute	.37
2) 5 minutes	.20
52100 steel in CAM 2 for:	
1) 1 minute	.20
2) 5 minutes	.17
52100 steel in Turbo TJ-15	
1) 1 minute	.3
52100 steel in Turbo TJ-15	
1) minute	.41

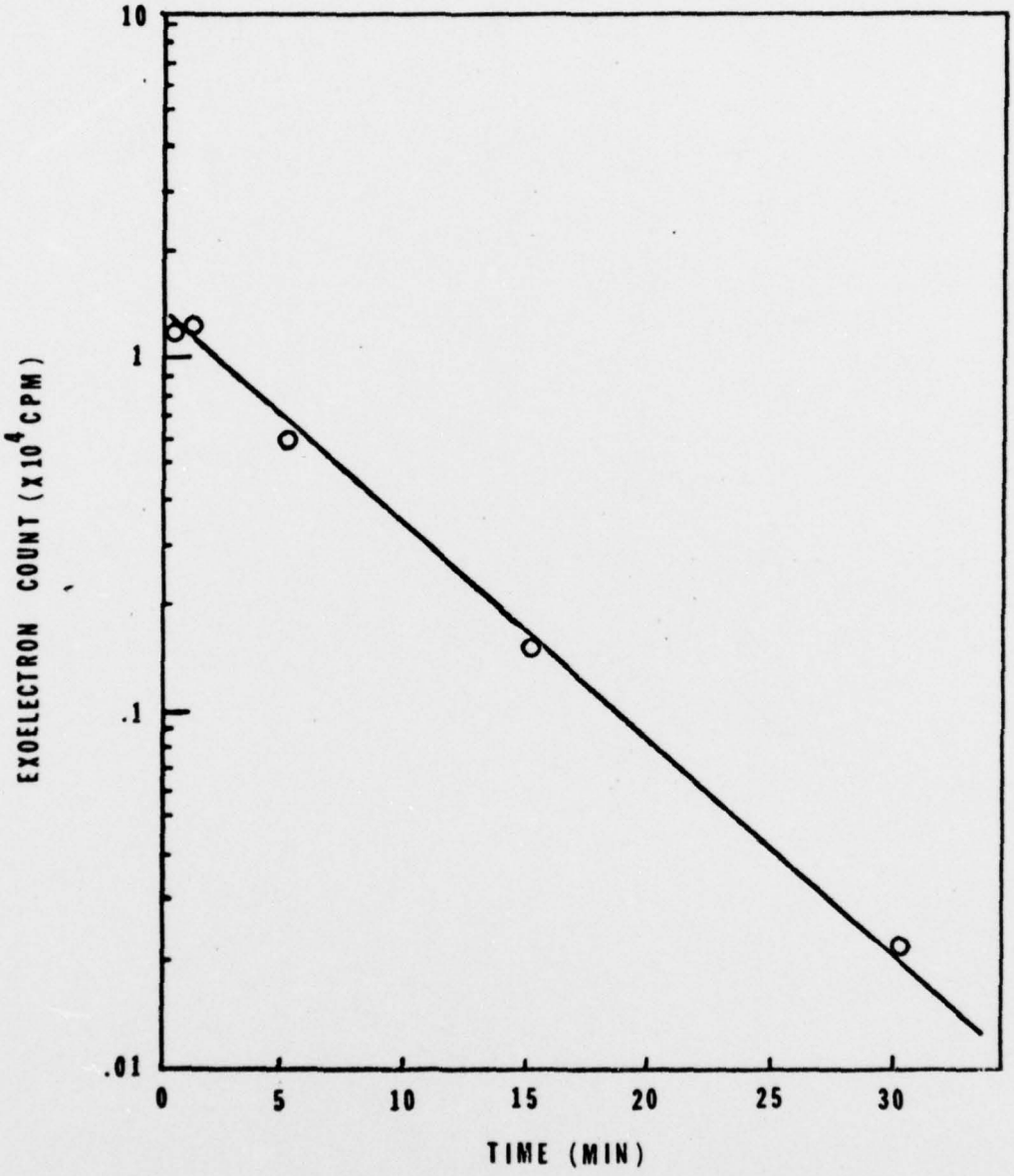


Figure 26 - EE rate versus lubricant immersion time from a scratched ball with lubricant bath at 25°C.

52100 bearing ball in Turbo TJ-15 at 25°C. The extrapolated value of N_o was 1.5×10^4 counts per minute (CPM). Similar results were obtained for the other lubricants and the N_o values are shown in Table 3.

TABLE 3

Bearing Material	Lubricant	$N_o (\times 10^4$ cpm)
52100 steel	Turbo TJ 15	1.5
Aluminum	Turbo TJ 15	3.0
Stainless steel	Turbo TJ 15	1.0
52100 steel	Nujol	2.5
52100 steel	CAM 2	2.5

Using these values of N_o a plot of $\ell n \ell n \frac{N_o}{N}$ versus $\frac{1}{\theta(°K)}$ was made for each test. Each data point on the graph is the geometric mean of the four scratch locations. The graphs of the test combinations using an immersion time of 1 minute are shown in figures 27-31.

The half life value of the EE decay in a lubricant can also be determined from the decay equation:

$$t_{1/2} = \frac{.693}{\lambda}$$

$t_{1/2}$ = half life time

λ = rate constant

The value of the rate constant can be calculated from equation 3 of section 2.4:

$$\lambda = \frac{\ell n \frac{N_o}{N}}{t}$$

t = lubricant immersion time

The extrapolated values of N_o were also used for the half life calculations. Table 4 lists the rate constant λ and the corresponding half life for each lubricant at various temperatures.

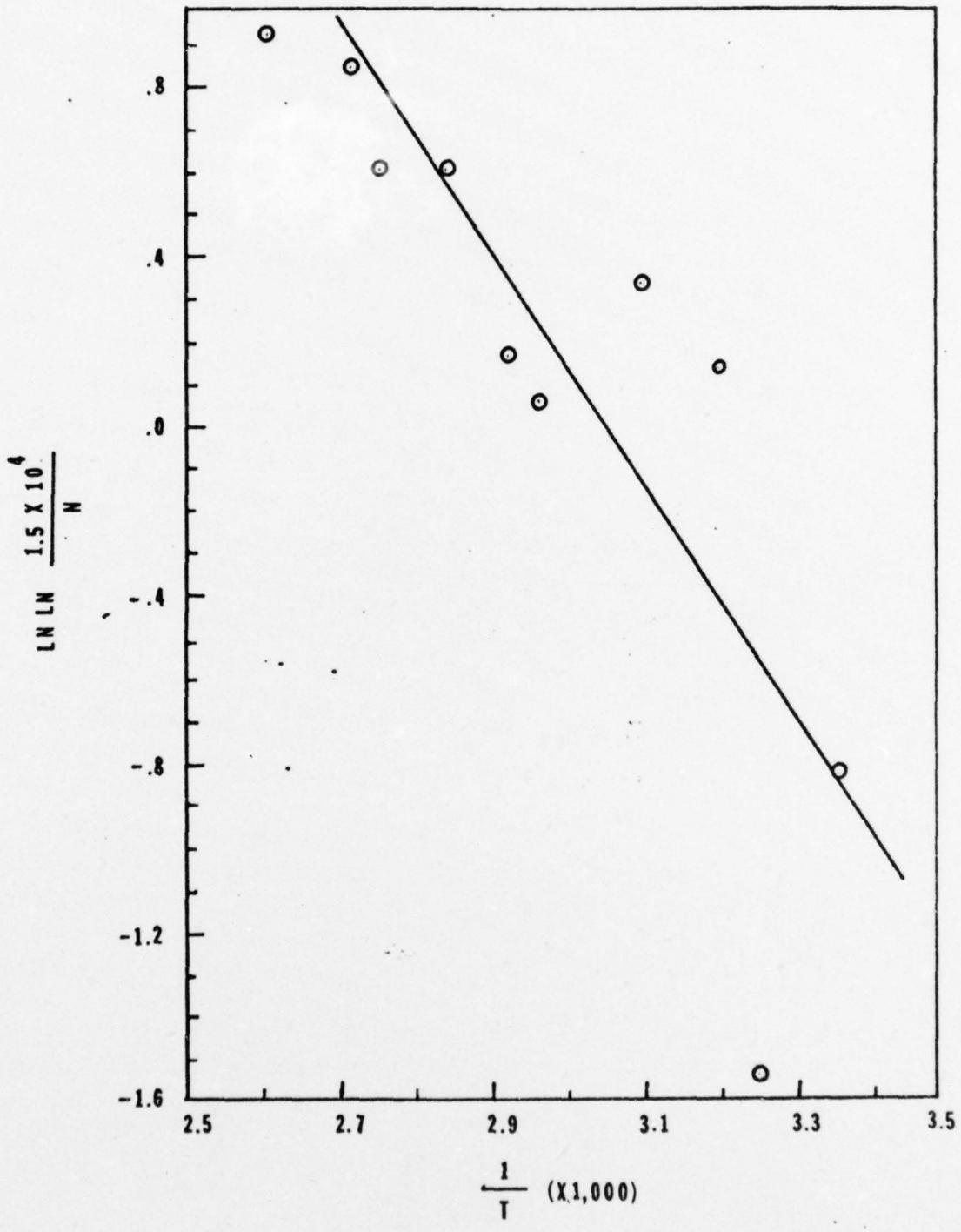


Figure 27 - $\ell n \ell n\ N_o/N$ versus 1/temperature (°K) for a scratched 52100 ball immersed in Turbo TJ 15 for 1 min.

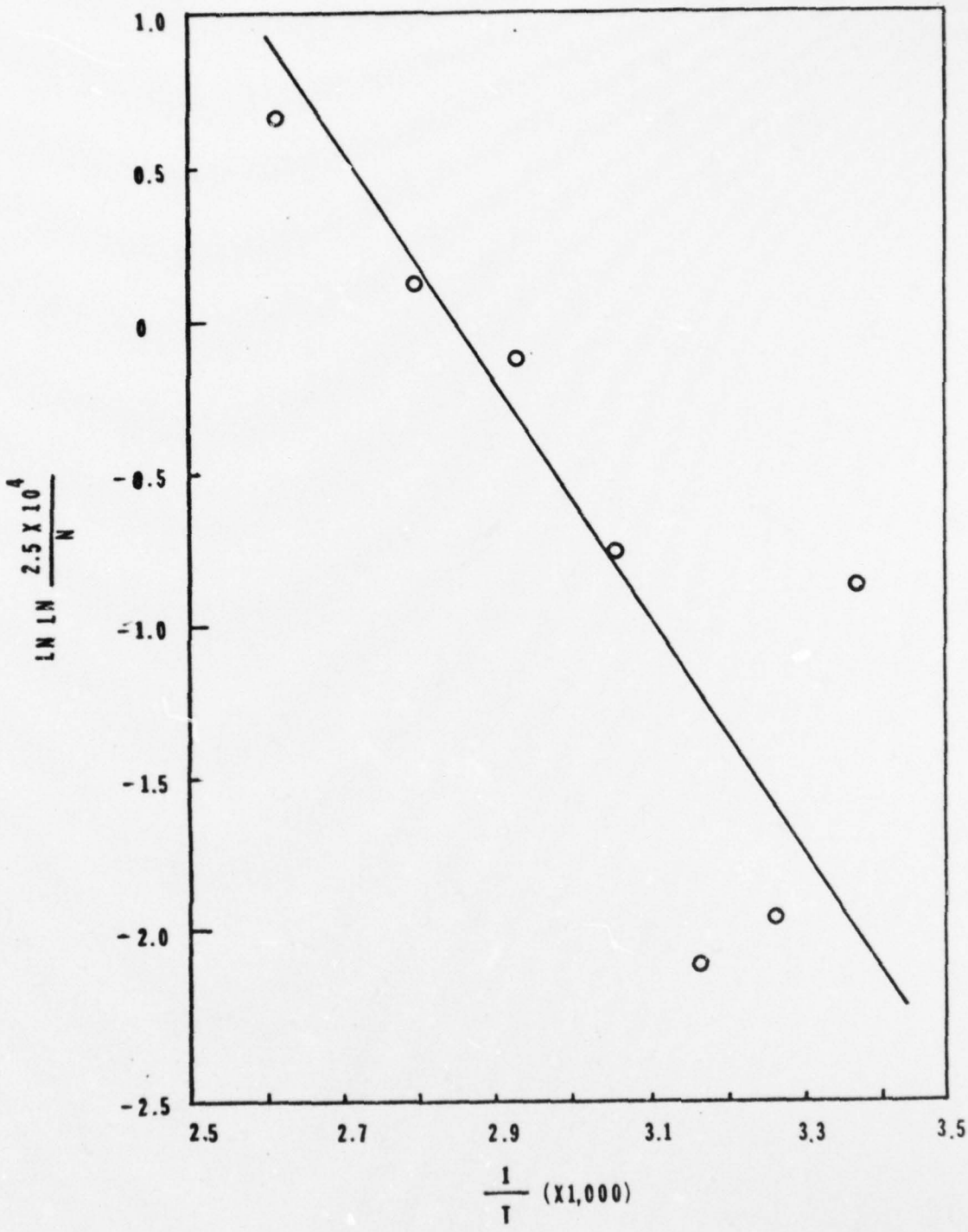


Figure 28 - $\ell n \ell n\ N_o/N$ versus 1/temperature (°K) for a scratched 52100 ball immersed in Nujol for 1 min.

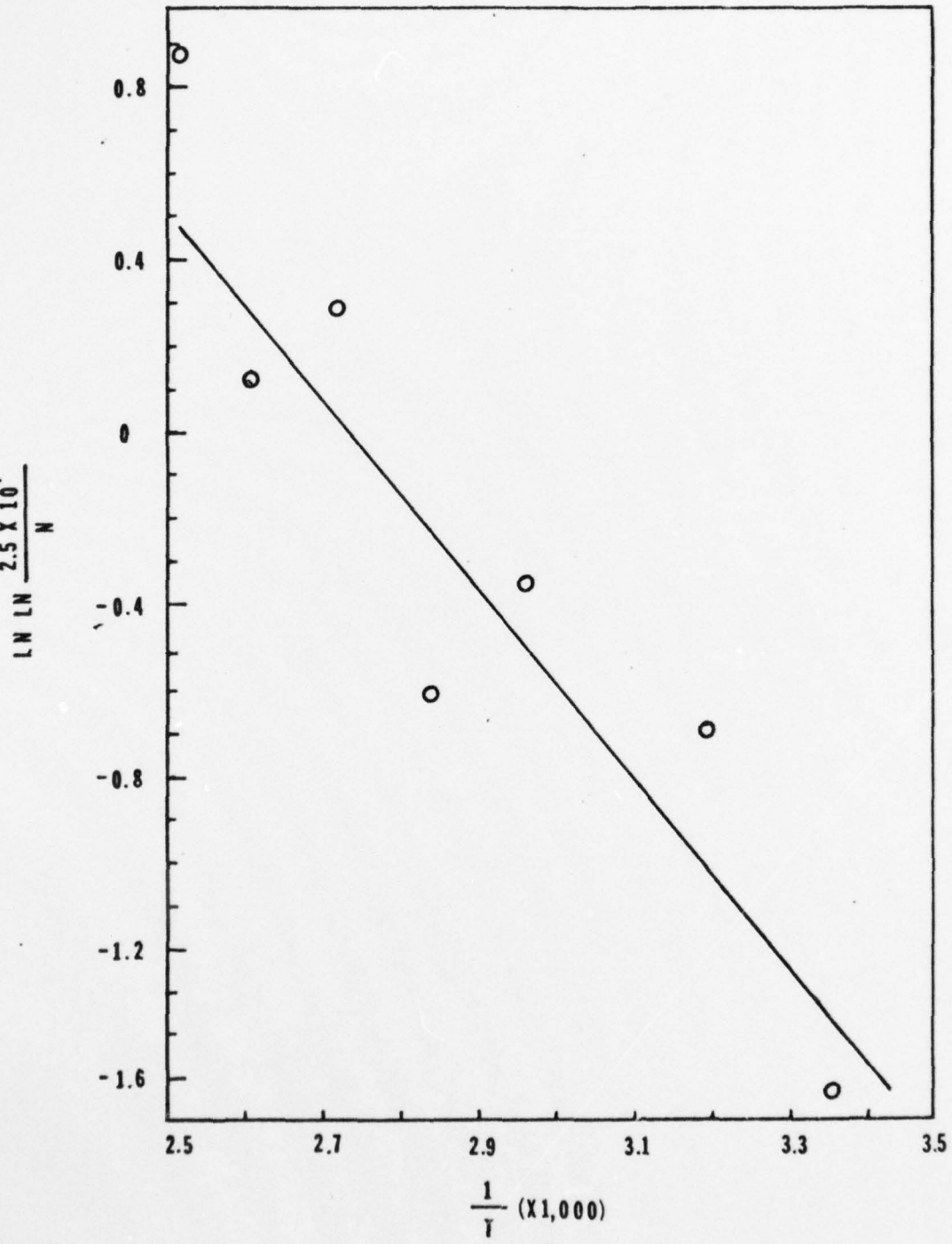


Figure 29 - $\ell n \ell n\ N_o/N$ versus 1/temperature (°K) for a scratched 52100 ball immersed in CAM 2 for 1 min.

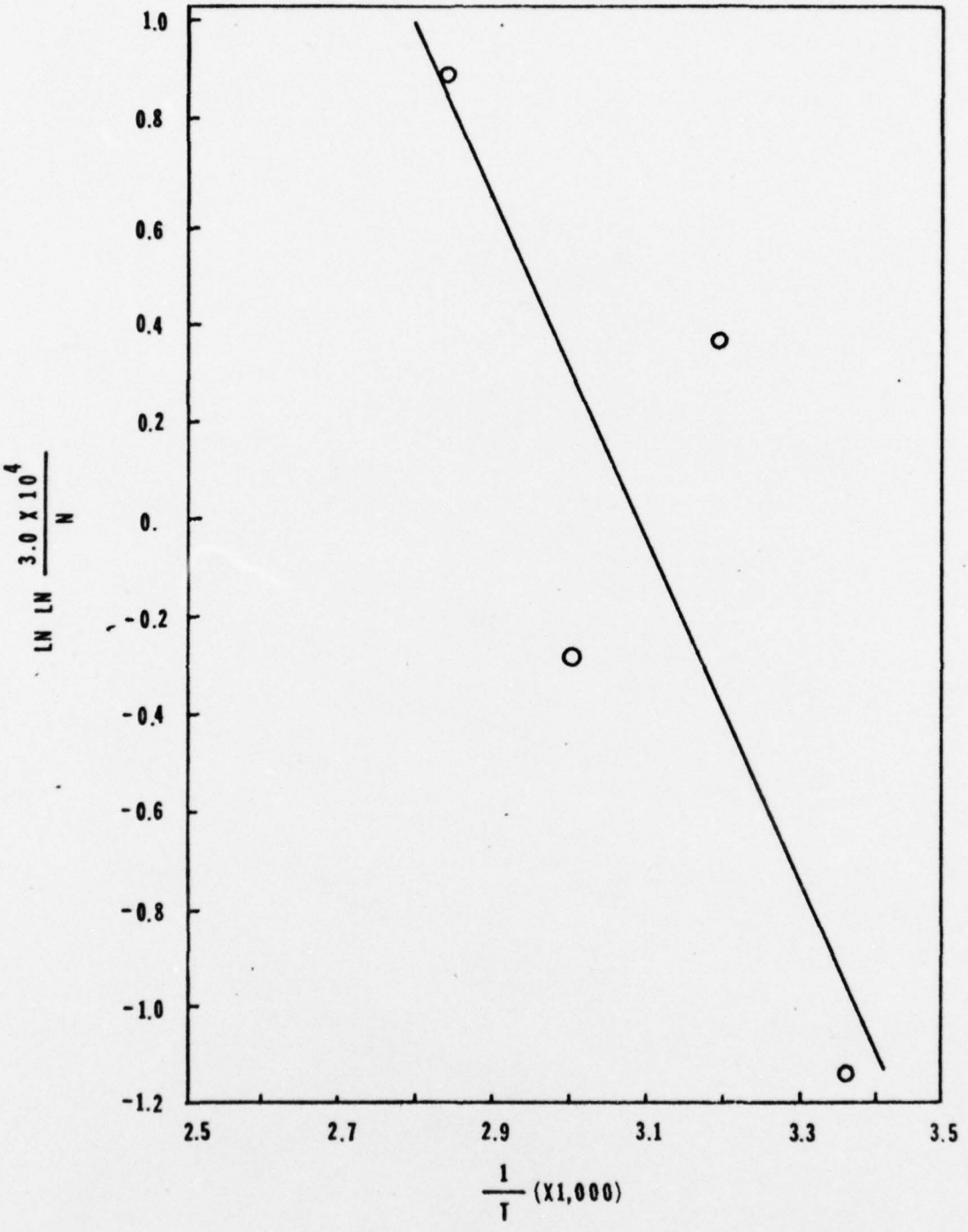


Figure 30 - $\ell n \ell n\ N_o/N$ versus 1/temperature (°K) for a scratched aluminum ball immersed in Turbo TJ-15 for 1 min.

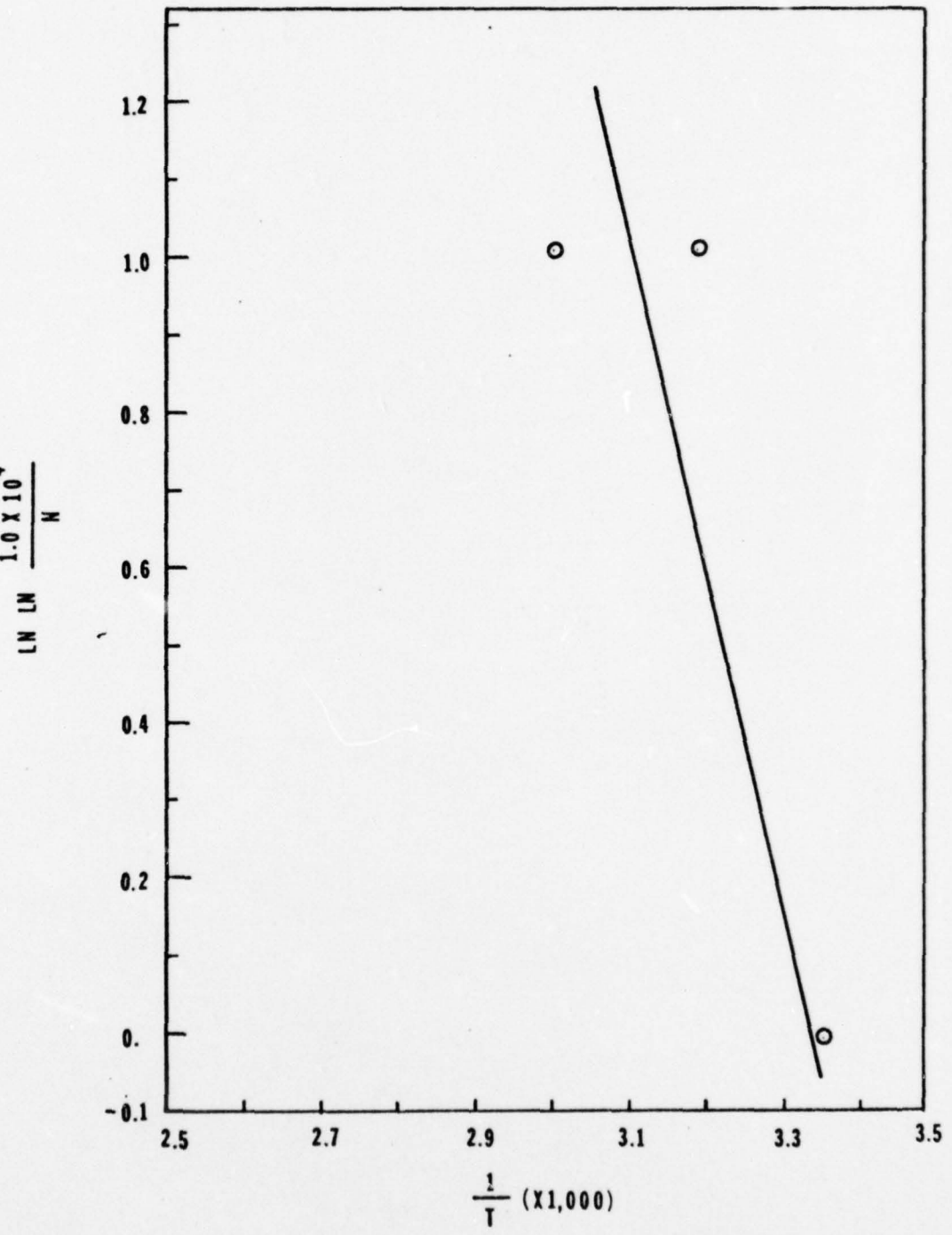


Figure 31 - $\ell n \ell n\ N_o/N$ versus 1/temperature (°K) for a scratched stainless steel ball immersed in Turbo TJ-15 for 1 min.

TABLE 4

Type of Lubricant	Temperature of Lubricant (°C)	Rate Constant $\lambda(min^{-1})$	Half Life $t_{1/2}(min)$
Turbo TJ-15	25	0.18	3.85
	40	0.28	2.47
	65	1.72	0.41
	580	2.30	0.3
Nujol	30	0.22	3.11
	55	0.46	1.5
	70	0.87	0.8
	95	1.11	0.62
	110	1.91	0.36
CAM 2	25	0.193	3.59
	40	0.446	1.55
	65	0.639	1.00
	95	1.20	0.58
	125	2.19	0.3

6.4 Discussion

These tests show that the decay of exoelectrons from a scratched metal surface is influenced by the environmental conditions. Results of this section show that the decay of exoelectrons is increased by the presence of air and of a lubricant.

In air, the decay of EE (figure 25), is approximately 30 times faster than the decay of EE in a vacuum, (figure 24). The slow EE decay rate in a vacuum explains why fatigue tests run in a vacuum have given the best results in terms of failure prediction. However, even in air, the initial EE rate drops by only 50% after 1.7 hours. This makes it easy to obtain a good electron detection signal from fatigue tests run in air.

The second section of the test program determined the influence of a lubricant, and the results showed that a lubricant greatly increases the decay rate of EE.

The computed activation energy values indicate the energy required to interfere with the ability of a surface to emit an exoelectron. Previous researchers have related the activation energy of exoelectrons to the initial stages of oxidation, diffusion of vacancies and chemiemission [1, 2].

Using the plot of EE rate at a scratch versus immersion time in the lubricant, the activation energy was calculated to be in the range from .14 to .41 eV. These are in the same range as the activation energy obtained by Pimbley and Francis [1].

Although the interpretation of the activation energy is not fully understood, the values do indicate that a reaction mechanism is present

at the metal-lubricant interface. This implies that the processes of oxidation, adhesion and adsorption are directly related to the EE decay rate.

The results of the lubricant test were also used to calculate the EE half-life. It was found that an increasing lubricant temperature decreases the half life time, (table 4) because the higher temperatures increase the reaction rate at the metal-lubricant interface. A comparison of the three different lubricants at 100°C shows that the half life times are all approximately 18 secs.

This finding has important practical consequences in the use of EE techniques to investigate spalling of lubricated surfaces. In order to avoid a great drop in EE, it is necessary to clean the lubricant off the fatigue specimen in a time short compared to 18 seconds. The specimen can then be placed in the vacuum detection chamber to further slow down the decay of EE. This procedure ensures that the best EE signal is obtained.

This series of tests establishes several important points. The decay of EE is slower in air than in a vacuum. However, the decay rate in both tests indicates that a measurable EE signal could be detected for long periods of time after fatigue tests. The addition of a lubricant at the site of exoelectron emission was found to greatly increase the decay rate. Half life calculations showed the importance of cleaning the lubricant off the fatigue specimen prior to EE detection. A more complete understanding of the exoelectron emission mechanism would help clarify the limitations of monitoring fatigue wear.

Three features of the fatigue tests are relevant to the EE decay

process. The most important component of the fatigue tests is that an area of EE be present on the surface of the ball bearing. The surface crack, a pit, dent, or plastic deformation are all possible sites of EE that occur on the ball prior to spall formation. Once the site of EE is present, the second feature becomes important. The load placed on the bearing ball results in lubricant temperatures reaching the 110 to 130°C range [7]. At these temperatures the half life of EE calculated from the lubricant tests is approximately 18 seconds. Therefore, the decay of EE in the lubricated fatigue conditions is very rapid. The third feature of the fatigue tests is related to the detection of the EE from a ball bearing surface. The minimum time between stopping the four ball tester and insertion into the EE detection chamber is approximately 5 minutes. Two minutes are required to get the specimen out of the four ball rig and into a cleaning solution. The ball is cleaned for three minutes and put in the detection chamber. Assuming an EE site is present on the ball bearing surface, by the time the lubricant is cleaned off, the EE decay has already been substantial. The poor correlation between the EE scans and the rolling contact fatigue process can be attributed to the lubricant decay effects.

CHAPTER 7

SUMMARY AND RECOMMENDATIONS

SUMMARY

Exoelectron emission is a potentially useful non-destructive method of monitoring rolling contact fatigue. In some cases it is possible to predict the site of spall formation based on peak emission sites. Scans made early in the life of the ball are more reliable for these predictions than scans made closer to the time of the spall. Studies of the leading and trailing edge of the spall provide an explanation for this occurrence. In the early scans, a peak is found at the leading edge of the future spall. Scans made midway through the tests show little difference between the two edges. Near the end of the tests the trailing edge registers a small peak. This indicates that crack propagation proceeds from the leading to the trailing edge.

Several of the tests showed no correlation between the emission data and the site of the spall. In some cases sub-surface cracks may have been involved. In other cases, environmental conditions, particularly the lubricant being used, apparently interfered with EE detection. A new series of tests was run to quantify the effects of lubricants on EE. At temperatures from 110-130°C, the emission decay was found to have a half life of 18 seconds when a lubricant was present. Since all rolling contact fatigue tests involved the use of lubricants, it was clear that bearing balls which were cleaned immediately after removal from the Barwell tester produced higher emission peaks than those which were handled more slowly.

7.2 Recommendations

Continued research into the use of EE to monitor rolling contact fatigue requires a different testing procedure. In order to obtain EE signals which can indicate localized emission sites on a ball bearing, two steps are necessary. First, the lubricant must be cleaned off the specimen immediately. Second, the specimen must be placed in a vacuum. Both steps are aimed at preventing the decay of EE and therefore produce better EE signal detection. These two steps can be implemented with the proper apparatus in a time period short enough to prevent the rapid decay caused by the lubricant.

The activation energy and half life calculations have given insight to the EE mechanism. The decay process of EE has been shown to be related to the metal-lubricant interface. This interface is where oxidation, adhesion, and adsorption take place. It is likely that EE used in lubricant research could result in a better understanding of the metal-lubricant interface. This in turn could lead to a better understanding of the exoelectron emission mechanism, which would aid in further developing its use as a non-destructive fatigue monitoring technique.

REFERENCES

1. Pimbley, W.T., E.E. Francis, "Effect of Temperature on the Emission of Electrons from Abraded Aluminum Surfaces," Journal of Applied Physics, Vol. 32, No. 9, September 1961, pp 1729-1733.

2. Brotzer, F.R., "Emission of Exoelectrons from Metallic Materials," Phys. Stat. Sol., 22, 1967, pp 9-30.

3. Sommer, A.H., Photoemissive Materials Preparation Properties and Uses, John Wiley and Sons, Inc., New York, 1968, pp 21-26.

4. Baxter, William, "Measurement of Surface Fatigue Damage by Exoelectron Emission," Metallurgical Transactions, Vol. 6A, April 1975, pp 749-754.

5. March, P., "Photostimulated Exoelectron Emission for the Nondestructive Study of Surface Fatigue Wear," M.I.T., S.M. Thesis, June 1975.

6. Rounds, Fred G., "Base Oil Effects on Fatigue Life for Additive Blends as Measured on a 4-Ball Fatigue Machine," ASLE Transactions, Vol. 20, No. 2, 1977, pp 115-125.

7. Syniuta, W.D., and C.J. Corrow, "A Scanning Electron Microscope Fractographic Study of Rolling Contact Fatigue," Wear, Vol. 15, 1970, pp 187-199.

8. Momose, Y., H. Okazaki, "Influence of Organic Vapours on Exoelectron Emission from Iron Surface Exposed to Discharge," Japanese Journal of Applied Physics, Vol. 12, No. 12, December 1973, pp 1890-1895.

9. Ramsey, J.A., G.F.J. Garlick, "Sensitized Photoelectric Emission During Oxidation of Aluminum," British Journal of Applied Physics, Vol. 15, 1964, pp 1353-1360.

10. Ramsey, J.A., "The Emission of Electrons from Aluminum Abraded in Atmospheres of Air, Oxygen, Nitrogen, and Water Vapour," Surface Science, Vol. 8, 1967, pp 313-322.

11. Tamai, Y., M. Suzuki and Y. Momase, "The Effect of Exoelectron on the Adsorption and the Lubricity of Hydrocarbon Liquids on Steel," Symposium on the Chemistry of Lubrication Presented before the Division of Petroleum Chemistry, Inc. and The Division of Colloid and Surface Chemistry American Chemical Society, San Francisco Meeting, April 2-5, 1968, pp B159-B162.

12. Tamai, Y., Y. Sato, Y. Momase, "Exo-Electron Phenomena and Adhesion of Plastic Film," Proceedings of the Fifth International Congress on Metallic Corrosion, 1974, pp 640-644.

VOLUME 20, 4, 315-320
ASLE TRANSACTIONS

Appendix I

Exoelectron Emission for the Study of Surface Fatigue Wear

P. A. MARCH* and E. RABINOWICZ (Member, ASLE)
Massachusetts Institute of Technology, Cambridge, Massachusetts 02139

An apparatus has been constructed for studying exoelectron emission from steel bearing balls which have been run in a Barwell four-ball surface fatigue wear tester. The test ball is periodically removed from the tester, cleaned to remove its oil film, transferred to a vacuum chamber, and illuminated by ultraviolet light. The emitted exoelectrons originating at new surface area generated on the ball during fatigue testing are detected by an electron multiplier. By rotating the ball and measuring the exoelectron emission as a function of position, the source or sources of the emission can be localized. The resolution of the research apparatus is presently limited to 0.27 mm, the width of the scanning spot. Exoelectron emission decay results indicate a relatively slow drop in emission with time. Preliminary results indicate that the fatigue failure occurs at one of several sites which have given enhanced electron emission.

INTRODUCTION

Rolling contact elements, such as ball bearings, roller bearings, cams, and gears are used in a wide variety of mechanical devices, because they operate smoothly and with low friction losses over extended periods of time, without undergoing any of the ordinary forms of wear, namely adhesive wear, abrasive wear or corrosive wear (*1*). However, their life is generally terminated by a unique form of wear, surface fatigue wear. During operation, suddenly and without warning, a large particle will be spalled from a bearing surface, and total failure of the element can occur in a very short time thereafter.

Several aspects of surface fatigue wear contribute to the difficulty in designing rolling contact elements. For a batch of 100 apparently identical ball bearings tested under identical test conditions, variations in ball bearing life by factors of 100 to one between the first and last failure are not uncommon. Also, no fatigue limit stress exists for surface fatigue wear (*2*). Because of the large scatter in life data and the absence of a fatigue limit stress, ball bearings must be severely de-rated in order to obtain reliable performance.

Despite the importance of surface fatigue wear, few satisfactory ways of studying it have been developed. The traditional technique consists of testing bearings to failure, and studying the effect on the life of changing parameters such as load, speed and lubricant. Furthermore, the spalled area is studied to determine metallurgical or other changes (*3*), (*4*). A different approach is to attempt to carry out measurements of a bearing before failure occurs, and in this way to obtain additional information both on the life of the bearing, and on the fatigue wear process itself. Two techniques in particular have been developed. Acoustic emissions have been used in several ways to study metal fatigue (*5*), (*6*), and a magnetic perturbation technique can also be used to detect the location and size of nonmetallic inclusions and voids in ferromagnetic materials (*7*). In this paper, a third technique of studying the pre-spalling stage of the fatigue wear process is described—that involving the detection of emitted exoelectrons from the bearing surfaces.

THE EXOELECTRON EMISSION PROCESS

Although the phenomenon now called electron emission was first reported by Moser (*8*) over a hundred years ago, the first systematic and detailed research in this field was performed by Kramer (*9*), and he coined the word "exoelectron." An extensive literature on exoelectron emission is available, and several excellent reviews of this literature have been written (*10*), (*11*).

Exoelectron emission occurs when a material's surface is disturbed in one of a variety of ways, including abrasion (*9*), (*10*), (*11*), phase transformation (*12*), plastic deformation (*13*), (*14*), and fatigue cracking (*6*), (*9*), (*14*), (*15*). The intensity of exoelectron emission can be increased by supplying energy to the emitting surface in a

*Now at Alden Research Laboratories, Holden, Massachusetts 01520

Presented at the 31st Annual Meeting
in Philadelphia, Pennsylvania, May 10-13, 1976

variety of ways, the most effective one being irradiation by ultraviolet light (*16*).

Exoelectron emission from a freshly formed surface reaches a maximum almost immediately, then decays with time (*10*), (*11*), (*17*). Researchers have observed exoelectron emission from both metals and nonmetals, and there is strong evidence that the existence of oxides or other nonmetallic surface layers is necessary for exoelectron emission. Although the exact mechanism or mechanisms of exoelectron emission still remain undetermined, researchers have been able to use exoelectron emission to study a variety of phenomena, including plastic deformation (*18*) and sliding friction (*19*). Of particular interest to this research are the techniques and results from studies using exoelectron emission to investigate fatigue.

In 1954, Koch (*20*), following the earlier work of Kramer (*9*), measured exoelectron emission from aluminum plates subjected to cyclic stresses and found that emission increased with the number of cycles. A more successful approach was that taken by Veerman (*14*), who used a small (0.5 micron) spot of intense ultraviolet light to traverse test specimens and then to measure photostimulated exoelectron emission, and in this manner, was able to map plastically deformed and cracked surfaces in steel and aluminum with a magnification of up to 1,000X.

Baxter (*13*), (*15*) developed a scanning apparatus in which a small spot of ultraviolet light and an electron multiplier were used to detect localized regions of increased exoelectron emission during fatigue cycling of aluminum and steel specimens. The intensity of this localized emission increased continuously with continued fatigue cycling, and final failure always occurred in the region of most intense emission.

This past research, using exoelectron emission to study bulk fatigue in various metals, suggested the possibility that exoelectron emission could be applied as a technique for studying surface fatigue wear. The main problem anticipated was that rolling contact bearings are generally operated in the presence of a lubricant, while exoelectron measurements are best carried out on a clean surface in a vacuum environment. Another possible problem lay in the fact that exoelectron emission susceptibility decays rapidly, thus allowing little time to clean a rolling bearing component and introduce it into a vacuum. However, the potential advantages of developing a new method of studying surface fatigue wear seemed so great that it was decided to construct and operate an exoelectron detection apparatus specially designed for operation with bearing balls.

EXPERIMENTAL APPARATUS

The experimental apparatus was constructed for monitoring the emission of exoelectrons from the surface of a single bearing ball, and the following is a typical sequence of operations. The test ball is inserted in a rolling contact fatigue tester and run at a known stress level. Periodically throughout the life of the test ball, it is removed, cleaned, and inserted in a vacuum chamber. There, the wear track is illuminated with ultraviolet light, and the exoelectron emission is measured and recorded as the specimen is slowly rotated. When the scan is completed, the ball is removed from the vacuum chamber and reinserted in the fatigue apparatus. This procedure is repeated until the test ball experiences a surface fatigue failure. The failure time and location are then compared to the previously observed exoelectron emission.

The fatigue tester was of the Barwell 4-ball type as used in recent rolling contact surface fatigue wear studies in the authors' laboratory (*3*), (*4*). A cross-sectional view of the test section is depicted in Fig. 1. The $\frac{1}{2}$ in. diameter test ball, held by a spindle and rotated at 3,560 rpm, rides on three lower $\frac{1}{2}$ in diameter balls. The three lower balls are separated by a fibrous spacer, and are constrained by a ring and disk to travel in a circular track. The lubricant is dripped continuously into the test section. A microphone attached to the four-ball tester transmits failure noise to instrumentation which automatically shuts off the power to the spindle motor, drops the loading weights, and stops an elapsed time clock. The geometry is such that contact is confined to a relatively narrow track on the upper ball, and damage and failure generally occur there. Thus, only this region need be monitored.

The vacuum exoelectron detection apparatus uses short-wavelength ultraviolet light to provide an effective means for the photostimulation of exoelectron emission. An ultraviolet lamp (primary emission at 2,537 Å) is the light source. The ultraviolet light passes through a quartz

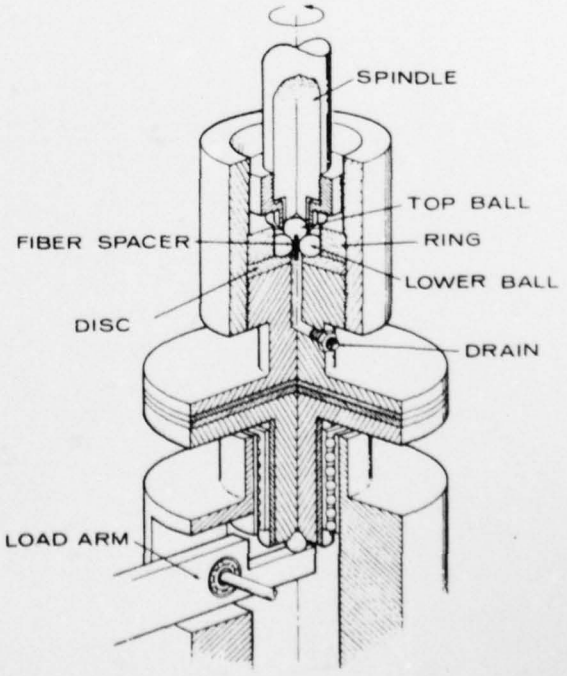


Fig. 1—Illustration of the Barwell 4-ball tester

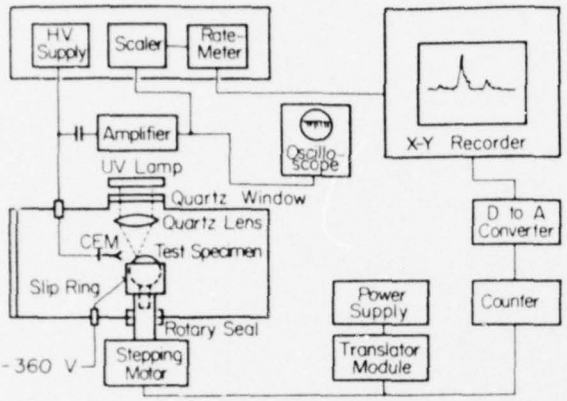


Fig. 2—Schematic illustration of the apparatus used for detecting exoelectron emission from a ball surface.

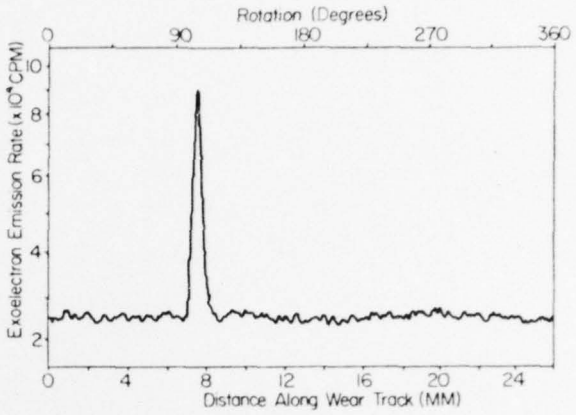


Fig. 3—Stimulated exoelectron emission as a function of position for a ball rotated in the detection apparatus shown in Fig. 2. The location of a scratch in the ball surface is easily seen.

window and is focused on the test specimen with a quartz lens, as shown schematically in Fig. 2. For the results given in this paper, the spot size was 2 mm x 0.27 mm and the estimated spot intensity was 1.5 milliwatts/cm^2. The emitted electrons are detected in an electron multiplier, which is basically a hollow glass tube with the inside surface coated with a semiconducting material which serves as the secondary electron emitting dynode surface. The output pulses indicating electron emission events are summed, and then displayed on the y-axis of an x-y recorder. A schematic of the exoelectron detection instrumentation is included in Fig. 2.

In order to ensure that the test specimen can be repeatedly inserted in the same position into the scanning apparatus, the test ball is fitted with a shaft having a milled flat which rests againsts a set-screw in the specimen holder. A stepping motor, coupled to a rotary vacuum feedthrough, rotates the specimen holder and the specimen in small discrete steps of 0.9 degrees/step (400 steps/rev.). The rotary position of the test specimen is recorded on the x-axis of the x-y recorder. Further details may be found in March's thesis (*22*).

EXPERIMENTAL RESULTS

Preliminary tests A variety of measurements were made of the exoelectron emission from a scratched or abraded area on the surface of a material. For example, a ½ in dia. 52100 steel ball bearing was cleaned with Freon degreaser, and a small scratched area was formed with a diamond scriber. The specimen was then inserted in the vacuum chamber, and the roughing pump was switched on until a vacuum of 5 x 10^{-4} torr was reached, the high voltage supply was turned on and the CEM was allowed to stabilize. The stepping motor was switched on, and exoelectron emission versus position was recorded on the x-y recorder.

Figure 3 shows the curve of photostimulated exoelectron emission (PSEE) versus position. It will be seen that there is a sharp peak in the emission rate when the ultraviolet light illuminates the scratched region on the ball. The drop with time of electron emission rate is presented in Fig. 4. For steel specimens the activity drops by about a factor of two in one day. With aluminum specimens, on the contrary, the exoelectron emission is far more vigorous, but drops by about a factor of two every half hour after a new surface has been formed.

Similar results to Fig. 3 were obtained with balls which were abraded when immersed in a lubricant, the lubricant cleaned off with a solvent, and the ball then placed in the vacuum chamber. The position of the scratch could be readily detected by the increased exoelectron emission rate.

Four-ball test results A number of fatigue wear test runs have been carried out using 52100 and M50 steel balls, but only one will be presented in detail. In this test, 52100 steel balls were run in the Barwell tester in the

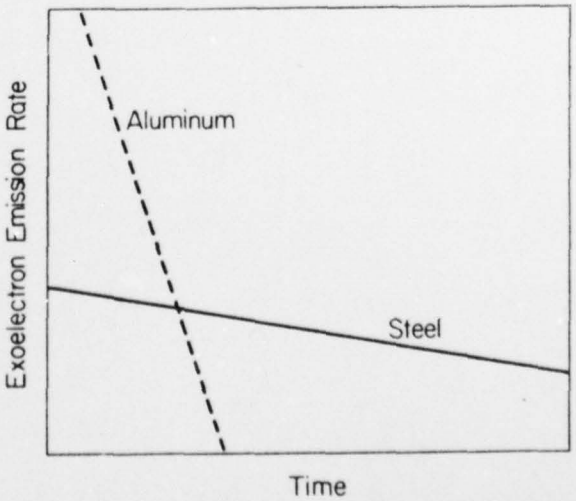


Fig. 4—Schematic illustration of exoelectron emission rates as a function of time observed with aluminum and steel specimens. Aluminum gives much higher initial emission rates, but the decay rate is much higher.

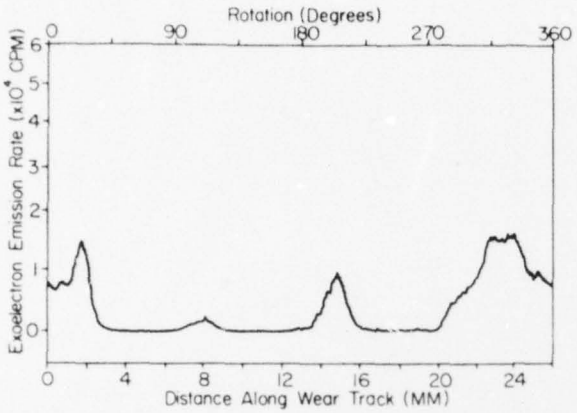


Fig. 5—Exoelectron emission as a function of position for a 52100 bearing ball before testing in the 4-ball tester at a load of 800 lb. There are a few low peaks visible.

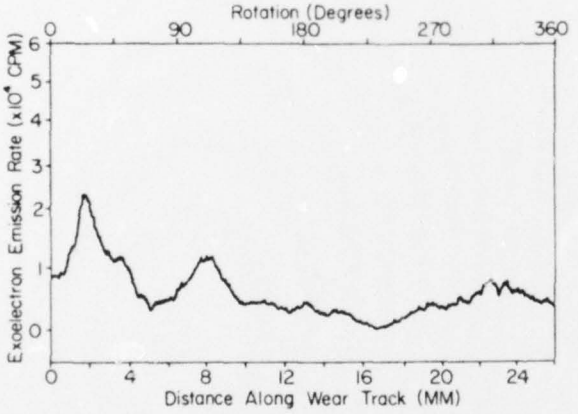


Fig. 6—Exoelectron emission from the ball shown in Fig. 5 after 10 minutes in the 4-ball tester.

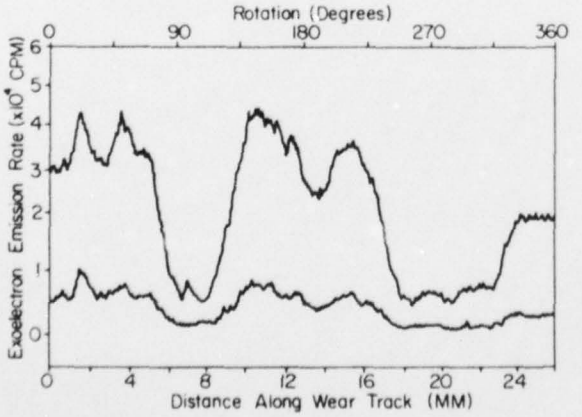


Fig. 7—Exoelectron emission at two different gain settings from the ball shown in Figs. 5 and 6, after 20 minutes in the 4-ball tester. Three prominent peaks have developed, at 1.5, 3.5, and 10.5 mm along the wear track.

usual manner, but at a high stress level in which the anticipated life was about 60 minutes, and the top ball was removed at intervals of about 10 minutes and tested for exoelectron emission and then run again in the tester. The test ball spalled after a total of 34 minutes of testing. In Figs. 5 through 8, PSEE scans for the 52100 test specimen are presented. These scans were taken at pre-testing, after 10 minutes, after 20 minutes, and after spalling. As will be seen, Fig. 7 indicates an exoelectron electron emission peak at the eventual spall site (as indicated in Fig. 8).

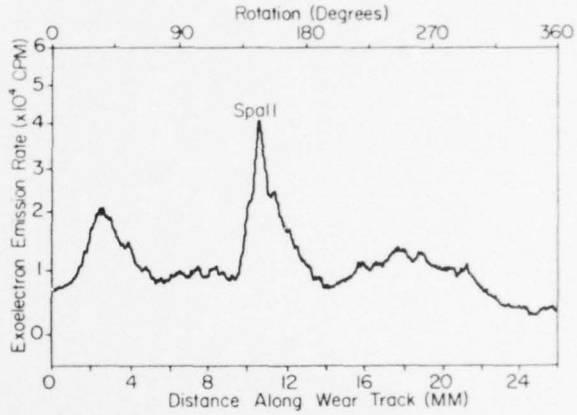


Fig. 8—Exoelectron emission from the ball shown in Figs. 5–7, following its failure by spalling after 34 minutes in the 4-ball tester. The site of the spall is indicated by a high peak at 10.5 mm along the wear track, at the same location as one of the three peaks in Fig. 7.

DISCUSSION

From the present tests, there is no conclusive evidence that a pre-test exoelectron emission scan can reveal an eventual failure site. The preliminary evidence based on but a few successfully completed tests, suggests that there is an increase in exoelectron emission during testing from a number of sites, about three in each of the authors' tests. The eventual spall location was in each case one of these sites. One of the problems may be that, during the initial portion of a test in the Barwell machine, metal-metal contact of the balls can occur. Any adhesive wear at this point will give enhanced electron emission almost indistinguishable from that due to crack growth.

The initial research reported here is promising, in that it suggests that exoelectron emission could become a valuable technique for studying surface fatigue in the pre-spall stage. This is particularly important because some promising techniques of accelerated life testing presuppose the availability of deterioration monitoring techniques. Furthermore, it may become possible to develop an exoelectron emission technique for predicting bearing performance and selecting out poor bearings and components. Using angular contact bearings for example, their orientation in a rolling contact device can be controlled by forming flats on the bearing balls, so that it would be necessary to measure exoelectron emission only

along a known track. Those bearings exhibiting excessive exoelectron emission would be automatically rejected by the scanning device.

SUMMARY

A procedure has been developed for studying the exoelectron emission from bearing balls. The anticipated problems arising from the fact that rolling contact testing is done on lubricated surfaces, while the exoelectron examination of surfaces is best carried out on clean surfaces in an evacuated chamber, did not arise. Stimulated exoelectron emission is a valuable research tool for answering such questions as whether ball bearing cracks originate at the surface of below the surface, and shows promise of becoming a technique helpful in accelerated life testing. Eventually, it may form the basis for a practical method for selecting out short lived bearings from a batch of nominally identical bearings.

ACKNOWLEDGMENTS

This work was carried out under contract DAHCO4-74-C-0028 sponsored by the U.S. Army Research Office—Durham, and the authors wish to thank Edward A. Saibel of that office for his advice and assistance. Messrs. R. Whittemore, G. Foote, and N. Mango of the Materials Processing Laboratory of M.I.T. have helped with the equipment and the electronic circuitry, while Ward Halverson of M.I.T.'s National Magnet Laboratory loaned us the electron multiplier used in this work.

REFERENCES

(1) Rabinowicz, E., "Friction and Wear of Materials," John Wiley & Sons, N.Y., 1965.
(2) Ref. (1), section 7.11.
(3) Reichenbach, G., and Syniuta, W., "An Electron Microscope Study of Rolling Contact," *ASLE Trans*, **8**, 217–223 (1965).
(4) Syniuta, W., and Corrow, C., "A Scanning Electron Microscope Fractographic Study of Rolling-Contact Fatigue," *Wear*, **15**, 187–199 (1970).
(5) Harris, D., and Dunegan, H., "Verification of Structural Integrity of Pressure Vessels by Acoustic Emission and Periodic Proof Testing," pp. 158–170, STP 515, ASTM, 1972.
(6) Moore, J., and Tsang, S., "The Early Detection of Fatigue Damage by Exoelectron Emission and Acoustic Emission," STP 515, ASTM, 113–157, 1972.
(7) Parker, R., "Correlation of Magnetic Perturbation Inspection Data with Rolling-Element Bearing Fatigue Results," *ASME J. of Lub. Tech.*, **97**, 151–158 (1975).
(8) Moser, R., *Pogg. Ann.*, **56**, 117 (1842).
(9) Kramer, J., "Der metallische Zustand," Göttingen: Vandenhoeck & Ruprecht, 1950.
(10) Brotzen, F., "Emission of Exoelectrons from Metallic Materials," *Phys. Stat. Sol.*, **22**, 9–30 (1967).
(11) Grunberg, L., "A Survey of Exo-electron Emission Phenomena," *Brit. J. of Appl. Phys.*, **9**, 85–93, March 1958.
(12) Hoenig, S., Savitz, C., Ott, W., Russell, T., and Ali, M., "Applications of Exoelectron Emission to Nondestructive Evaluation of Alloying, Crack Growth, Fatigue, Annealing, and Grinding Processes," *Testing for Prediction of Material Performance in Structures and Components*, ASTM STP 515, American Society for Testing and Materials, 107–125, 1972.
(13) Baxter, W., "A Study of Plastic Deformation by Exoelectron Emission," *Vacuum*, **22**, 571–575 (1974).
(14) Veerman, C., "Registration and Mapping of Plastically Deformed Metal Surfaces by Means of Photoelectrons," *Materials Science and Engineering*, **4**, 329–342, (1969).
(15) Baxter, W., "The Detection of Fatigue Damage by Exoelectron Emission," *J. Appl. Phys.*, **44**, 608–614 (1973).
(16) Grunberg, L., "The Study of Freshly Deformed Metal Surfaces with the Aid of Exo-electron Emission," *Wear*, **1**, 142–154 (1957).
(17) Ramsey, J., "Exo-electron Emission from Abraded Metal Surfaces at High and Ultrahigh Vacuums," *J. Appl. Phys.*, **37**, 452–453 (1966).
(18) Mints, R., Kortov, V., Plekhanova, E., Peshchin, G., and Semko, Y., "Investigation of the Nature of the Photostimulated Exoelectronic Emission in the Friction of weak-Current Precision Contacts," *Soviet Materials Science*, **8**, 281–283, June 1974.
(19) Evdokimov, V., "Investigation of Exoelectronic Emission of Surface Layers During Sliding Friction," *Soviet Physics-Doklady*, **13**, 475–477 (1968).

DISCUSSION

JOHN FERRANTE
NASA/Lewis Research Center
Cleveland, Ohio 44135

The authors are to be congratulated for preparing to apply the technique of photo-stimulated exoelectron emission to study surface fatique wear. It should have the potential of providing new information in understanding this phenomenon. There are several comments to be made concerning terminology, understanding the phenomenon, and the results of the paper.

The term exoelectron emission has become quite nebulous since it applies to many possibly unrelated phenomena. For example, a paper is being presented by Ferrante at this meeting that gives evidence for emission of electrons resulting solely from adsorption and/or chemical reactions of clean surfaces. The phenomenon in the present paper is of a different physical nature and should be referred to as enhanced photoemission or photoemission electron microscopy, a form which Baxter (*11*) who has done extensive similar research in this area) presently prefers. Changing and using more descriptive terminology could aid in eliminating the confusion that exists with the term exoelectron emission.

The paper suggests that this technique could be used for prescreening bearings for life. This seems unlikely since it depends on running the bearings to determine the areas of potential failure. It may, however, lead to a better understanding of failure mechanisms which may enable accelerated life tests, as suggested, and improved material selection and preparation. To accomplish this end, however, extensive testing and correlation will be necessary. It will also be necessary to have a better understanding of the physical mechanisms involved. For example, Baxter suggests that disruption of surface oxides are responsible for differences in electron emission. If this is the case, then it is surprising that any emission was observable, since the cleaning process and the transport and mounting time in the vacuum system should have been more than sufficient to have reoxidized the damaged areas. A long processing time may have been the reason that it was necessary to increase the gain on the electron multiplier in Fig. 7 in order to detect any emission. Better controls on the environment of the test specimen

and the use of analytical tools such as Auger Electron Spectroscopy would aid in understanding the phenomenon and establish its importance to wear.

REFERENCE

(*Al*) Baxter, William J. and Route, Stanley R., "Photoemission Electron Spectroscopy of Oxide Fracture at Slip Steps on Metals," *Journal of Applied Physics*, **46**, 6, 2429-2432 1975.

DISCUSSION

W. J. BAXTER

General Motors Research Laboratories
Warren, Michigan 48090

The authors are certainly grappling with a very difficult problem, namely the complexity of the spalling process itself in combination with the question of interpretation of the subsequent exoelectron emission. It is encouraging that emission is indeed observed from the eventual spalling site, and not surprising that there is also emission generated elsewhere since there will surely be other regions of less severe damage. As the authors point out the emission probably arises from two sources; namely, regions of abrasion as well as fatigue deformation and cracking. Since the emission from both these sources results primarily from the creation of a fresh metal surface, the emission will immediately decay quite rapidly due to reoxidation. The observation that the emission from the scratches (Fig. 4) decayed only gradually, indicates that the initial rapid stage of reoxidation was completed during the transfer of the specimen to the vacuum chamber. This effect may be important in the development of a quantitative assessment of surface fatigue wear by this technique.

AUTHORS' CLOSURE

The helpful discussion by Dr. Ferrante is appreciated. His comment on the vagueness of meaning nowadays associated with the term "exoelectron emission" is very well taken (the authors have encountered a wide variety of phenomena on looking up references on "exoelectrons" in various abstracting journals). However, they do not believe that much improvement in terminology is possible unless and until research workers in the field reach a consensus as to what physical phenomena are responsible for the emission of electrons in what circumstances.

It is true that, in order to use exoelectrons for the prescreening of rubbing interfaces, one would have to carry out realistic performance testing, and, in the case of ball bearings, this might involve an additional complex testing procedure to be carried out by the bearing manufacturer. However, there is another possibility. Almost all mechanical machines and devices involving moving components are dynamically tested by the manufacturer before they are shipped to users. If exoelectron testing becomes feasible, a new inspection procedure might be introduced after this dynamic testing.

The authors agree wholeheartedly with Dr. Baxter's comments on the complexity of the spalling and of the exoelectrons emission processes. The slow rate of decay of our exoelectrons was somewhat of a surprise to us, and a pleasant one at that. Incidentally, recent observations suggest that the exoelectron emission of a steel ball scratched in air decays faster in a period of some days if it is continually moved from air to vacuum and back again than if it is left in the authors' vacuum chamber after it is first introduced into it.

Appendix II

an Article from | SCIENTIFIC AMERICAN

JANUARY, 1977 VOL. 236, NO. 1

Exoelectrons

They are electrons emitted by a fresh metal surface. Such surfaces are created by wear or by the cracking associated with metal fatigue; thus exoelectrons have become useful in the study of those processes

by Ernest Rabinowicz

Investigators who want to study the surface of a metal for wear, cracks or other defects can call on a wide variety of techniques: optical microscopy, electron microscopy, scanning electron microscopy and autoradiography, among others. Thus a graduate student doing a doctoral dissertation on some aspect of surface science commonly ends up with a collection of lovely pictures and then finds it quite difficult to extract any numbers that can be plotted on curves, evaluated and tested critically. Furthermore, he cannot be sure that the regions visible in the pictures are truly representative of the surface as a whole. This unsatisfactory state of affairs is being remedied by a new technique that involves the detection of exoelectrons, electrons that are emitted from surface atoms under certain conditions that provide enough energy to provoke their release. It turns out that such conditions are closely correlated with the surface changes produced by wear, cracks and material fatigue in general. The exoelectrons can readily be counted, so that the technique provides what pictures normally lack: numbers that can be displayed, plotted and compared.

FATIGUE CRACK IN ALUMINUM looks like this in an optical microscope. Although optical and other standard imaging techniques are usually effective in revealing cracks and other surface flaws, they give no information about how recent they are or how they are progressing.

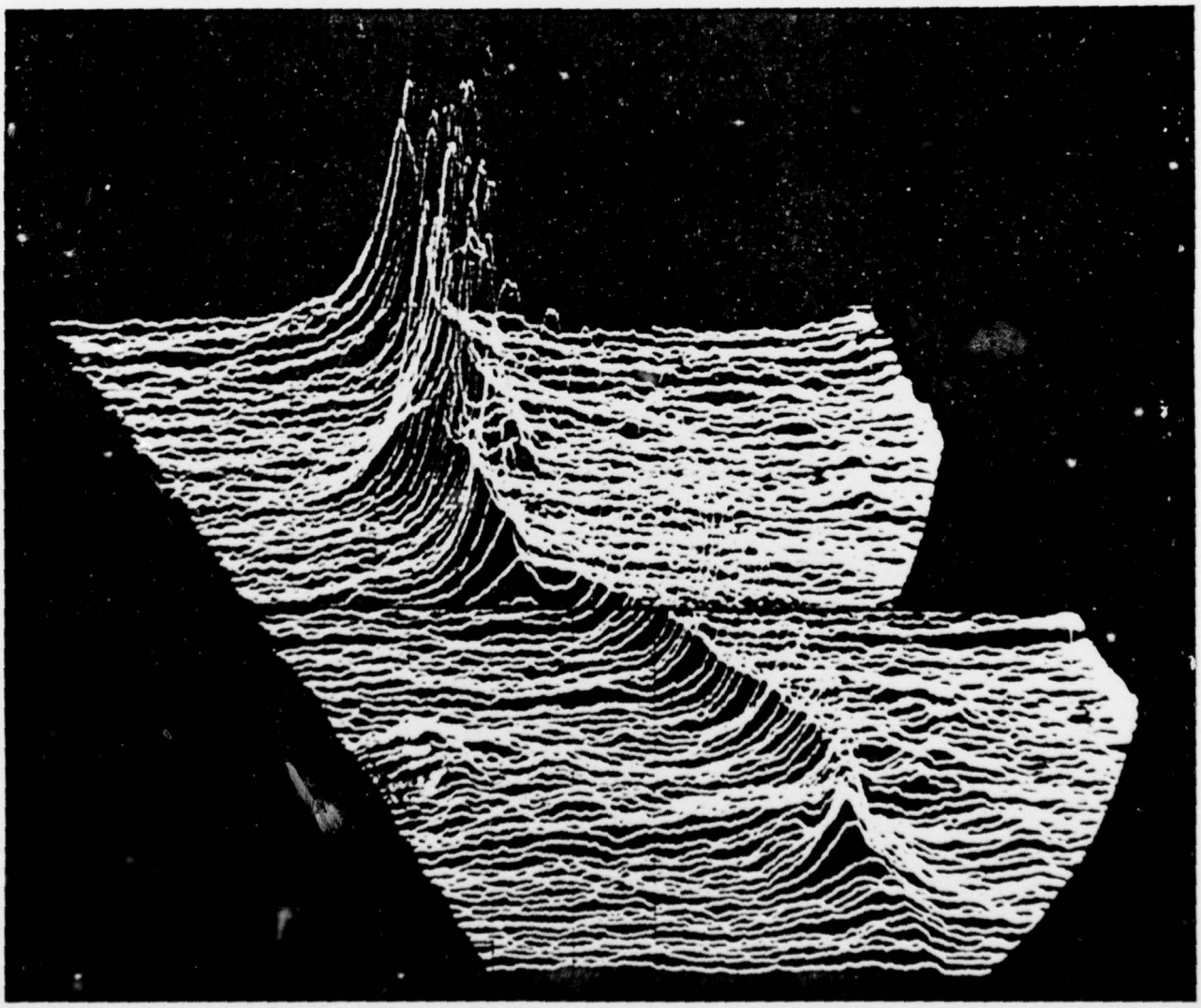
The discovery of exoelectrons is related to a malfunctioning of Geiger tubes, which are used to detect the radiation, particularly electrons, produced by nuclear reactions or the decay of radioactive nuclei. Geiger tubes are essentially metal cylinders, typically about the size and shape of a large cigar, with a fine insulated metal wire running down the middle and a thin foil window sealing off one end. A high-voltage difference, commonly 1,500 volts, is applied between the center wire and the grounded cylinder. If a high-energy electron enters the window, it triggers an electric discharge that can be recorded and counted. Soon after the introduction of the Geiger tube in the 1920's it was observed that a freshly made tube gave a high and irregular counting rate over the first few hours or days and after that performed normally. A little later it was found that when any freshly machined surface was introduced into a Geiger tube, that too increased the initial counting rate.

The phenomenon was first carefully investigated by a German physicist, Johannes Kramer, in the 1940's. He showed that all freshly prepared metal surfaces had the ability to give off electrons and that if the electrons were emitted inside a Geiger tube, they would of course trip the counting mechanism. Kramer found that the emitted electrons had an energy of only about one electron volt and that the emission lasted for only a few hours or days after the fresh surface was produced. Hence the increased initial counting rate of new Geiger tubes was finally explained.

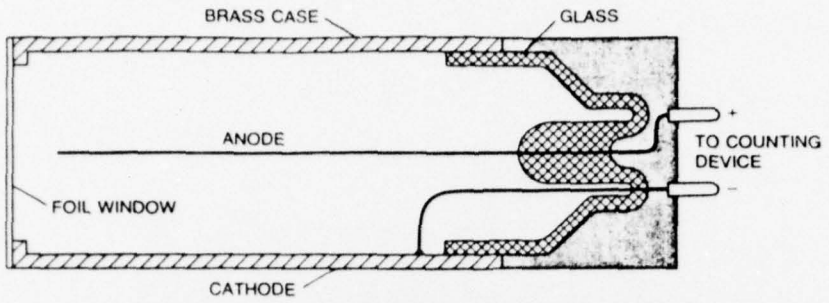
The announcement of this discovery surprised the physics community. The conditions under which electrons could be emitted from a metal surface had been well established for many years, as the result of studies that had become classic, and the phenomenon discovered by Kramer simply did not fit. Briefly, it was well known that in order to remove electrons from any surface a specific amount of energy had to be supplied. For a metal such as copper the removal of one electron requires the expenditure of 4.3 electron volts; therefore one speaks of the work function of copper as being 4.3 electron volts. One well-known method of removing electrons from a surface is to heat the surface to a high temperature, thus enabling an electron to acquire enough energy by thermal excitation to exceed the work function and leave the surface. The process is known as thermionic emission. Another method consists in shining ultraviolet radiation on the surface. If the wavelength of the radiation is short enough for the energy in each photon to exceed the work function, a photon can transfer its energy by colliding with an electron, and the electron springs from the surface. This process is known as photoelectric emission. (When Albert Einstein received his Nobel prize in 1921, it was for his 1905 paper explaining the photoelectric effect.)

Kramer's discovery of the spontaneous emission of electrons was surprising precisely because it described the spontaneous occurrence of something that was known to require the expenditure of considerable energy. A good analogy might be a housing development in a part of the country where the water table is 4.3 meters below the surface. To get water to the surface every householder has to drill a well at least 4.3 meters deep and pump the water up from that depth. Then someone comes along who drills a new well and finds that water spurts out of the ground spontaneously to the height of a meter!

What mechanism supplies the energy that is required to overcome the work function and cause the emission of an electron? Kramer thought the energy was thermal in nature. For example, if an old metal surface is abraded, its oxide layer is removed and a naked metal surface is left. The fresh surface would immediately start to oxidize again, lib-



EXOELECTRON IMAGE of the fatigue crack shown optically on the opposite page provides information that is both more graphic and potentially more useful. In general the fresher the surface is, the more exoelectrons are emitted. The exoelectron image shown here was made by scanning the aluminum surface with a fine beam of ultraviolet radiation, which stimulates the emission of exoelectrons. The intensity of emission is simultaneously displayed on the face of a cathode-ray tube by an electron beam that follows the scanning pattern of the ultraviolet beam. The vertical deflection of the cathode-ray image is proportional to the intensity of exoelectron emission. The exoelectron image and the optical image on the opposite page were made by C. C. Veerman of the Delft University of Technology.



ANOMALOUS BEHAVIOR OF GEIGER TUBES led to the discovery of exoelectrons. Perhaps the best-known detector of charged subnuclear particles, a Geiger tube consists of a metal cylinder surrounding a fine metal wire, which are insulated from each other so that a difference of about 1,500 volts can be applied between the two. When an electron or another kind of charged particle enters the tube through a thin foil window, it triggers a brief electric discharge. Such discharges can be recorded and counted. It had been observed that newly made Geiger tubes often give spuriously high counts for hours or days. The cause was internal exoelectrons.

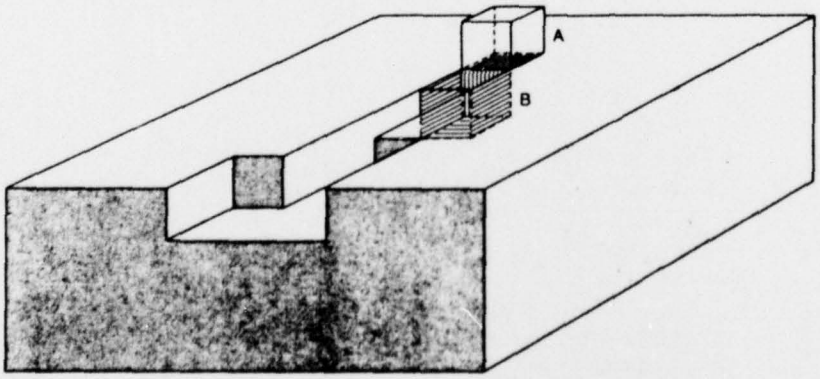
erating a considerable amount of chemical energy in the form of heat. Electron emission was also observed when a liquid metal cooled and solidified. There the latent energy of melting is given off in the form of heat, and conceivably some of the released thermal energy could give rise to the emission of electrons. Since such processes are exothermal, or heat-emitting, Kramer called the electrons exoelectrons. Although his explanation for the mechanism of electron emission is not accepted today (for example, the exoelectron emission in solidification is believed to be associated with changes in volume and the accompanying breakup of surface layers), the term exoelectron has survived. Exoelectrons are also, however, sometimes called Kramer electrons.

Kramer's book of 1950 describing his findings stirred up great excitement among investigators interested in surfaces, who perceived that exoelectrons might be useful in their work. Physicists also expended considerable effort trying to explain just how and why exoelectrons are produced. As a result exoelectrons were soon enlisted in the study of a wide variety of surface phenomena: friction, wear, metal-cutting, grinding, ball-milling, catalysis, corrosion, fracture, plastic deformation and many others. In addition there were numerous studies making use of physical and chemical techniques to elucidate the properties of exoelectrons and to discover the mechanism of their production. Some of this work was published; much was not.

I shall discuss the scientific and engineering aspects of exoelectrons in turn. Concerning the production of exoelectrons there can be no doubt that if a freshly machined metal surface is to give off an electron, there must be a source of energy. A freshly prepared surface has two obvious sources that an old surface does not have. One is the chemical-bond energy of the metal. Let us consider one greatly simplified way this energy could be made available. When a fresh surface is created by machining, an atom may be left in an exposed position, so that several of its chemical bonds are unsatisfied and, as it were, dangling. Later, when the atom forms new bonds with other atoms in the metal, the number of dangling bonds is reduced and the energy of the new bonds is made available, either in the form of heat or possibly in the form of exoelectrons. The other energy source is the one I have already described: the energy of oxidation or analogous processes.

One can estimate the amount of energy involved in each process. As an extreme example of the first case consider an atom of copper that is left dangling on a fresh surface so that it is held by a bond in only one direction, compared with the six directions in which it would be held if it were embedded in the crystal lattice of the metal. If the atom dropped into a nearby slot in the lattice, it might be held by bonds in four directions. In its initial state it was five-sixths of the way toward being evaporated (since an evaporated copper atom has no bonds to other copper atoms); after dropping into the slot it is only two-sixths evaporated (since we have assumed that bonds in two directions are still missing), so that the energy made available by the movement of the atom is the difference: three-sixths, or one-half, of the energy of evaporation of copper. The energy of evaporation of copper at room temperature is 2.9 electron volts per atom, and so we conclude that the energy resulting from the atomic rearrangement, being about half the energy of evaporation, might amount to 1.45 electron volts. Consider now the energy released by oxidation. If one atom of copper oxidizes to CuO (copper can also oxidize to Cu_2O with the liberation of a similar amount of energy), the energy liberated is .8 electron volt.

It is hard to see on the basis of these calculations how an exoelectron acquires the 4.3 electron volts it needs to overcome the work function and escape from a copper surface, to say nothing of the additional electron volt corresponding to the kinetic energy a typical exoelectron possesses. One possibility is that a copper atom might oxidize, adopt a more highly bonded lattice position and acquire an unusual amount of thermal energy all at the same instant. Another is that after the copper starts to oxidize, a very thin oxide layer with a reduced work function, say two electron volts, might be formed at the surface. This makes exoelectron emission easier because the energy requirement is re-



ONE THEORY OF EXOELECTRON EMISSION invokes the energy that is made available when an atom drops from a location in which it is loosely bound on a metal surface (*A*) to one where it is more tightly bound (*B*). In this schematic example the atom on the surface is bound in one direction only, to a neighboring atom below it, leaving it with free bonds in five directions. When the atom drops into a slot in the surface, it is held by bonds in four directions, leaving only two bonds free. Energy released in the change is roughly equivalent to about half the energy needed to evaporate the atom and could help to eject an electron from the surface.

duced, but at the same time the exoelectrons must now traverse the oxide layer in order to reach the surface. Another possible phenomenon to be considered is the adsorption onto the solid surface of gas molecules from the environment. Such adsorption could contribute energy, but the amount would be limited.

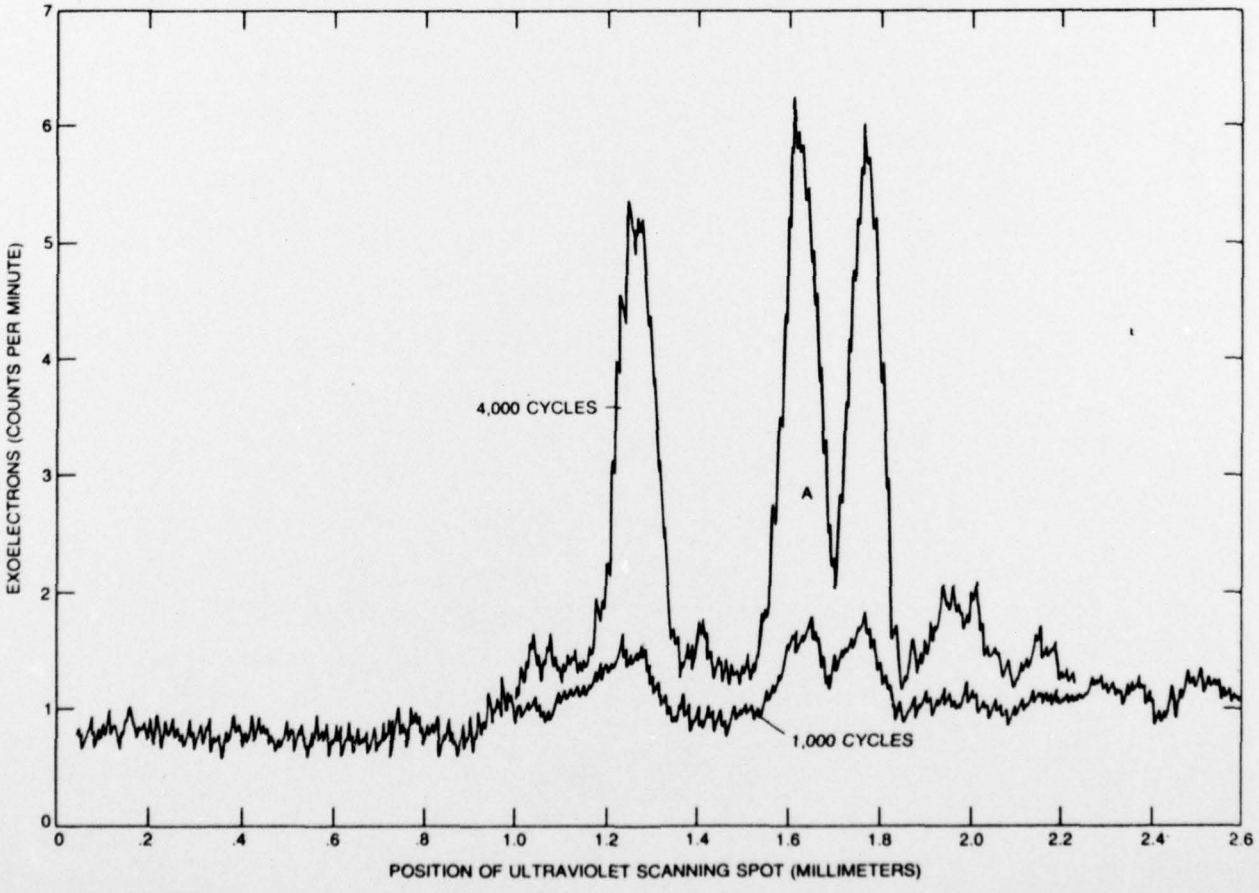
After considering such possibilities, one is left with the impression that exoelectron emission seems to depend on an unusual combination of favorable circumstances. In fact, calculations based on the rates of exoelectron emission confirm that the production of an exoelectron is a rare event. If one abrades a square centimeter of a metal surface, about 10^{15} metal atoms are exposed. If exoelectron emission were normal surface behavior, one might expect each surface atom to be the site for the emission of at least one electron, so that in the course of several days a total of 10^{15} exoelectrons might be emitted from each square centimeter of freshly exposed surface. The total number of exoelectrons is much smaller, amounting to no more than about 10^{8} per square centimeter even in favorable circumstances. Thus only about one surface site in 10 million sites is subjected to the special set of conditions required for the emission of an exoelectron.

So far every expert on exoelectron phenomena seems to have his own theory about the exact combination of conditions needed for exoelectron emission. One of the problems is that each worker runs his tests under somewhat different conditions, and he naturally finds that the results he gets do not quite match those of other workers. It seems likely that different combinations of the available mechanical energy, chemical energy, adsorption energy and thermal energy, balanced against a work function that changes as a result of chemical action and surface contamination, are operative in different circumstances.

The users of exoelectrons quickly found that exoelectron emission could provide information about many surface-related effects. For example, when a coarse material is put into a ball mill (essentially a rotating drum filled with steel balls) in order to reduce it to a powder, at first there is a steady reduction in the size of the particles but then the rate of reduction decreases and eventually levels off entirely. The phenomenon is faithfully mirrored by the rate of electron emission from the particles, which is fairly high in the early stages of the milling process but decreases steadily.

Another example is what happens when two metals are slid over each other under various loads: they emit more exoelectrons at high loads than at low loads. This was hardly surprising, since one would expect a greater surface area to be disturbed at high loads than at low ones. Although the correlation between exoelectron emission and load was interesting, no one could see any way to exploit the emission to gain a significant new understanding of the phenomenon of friction.

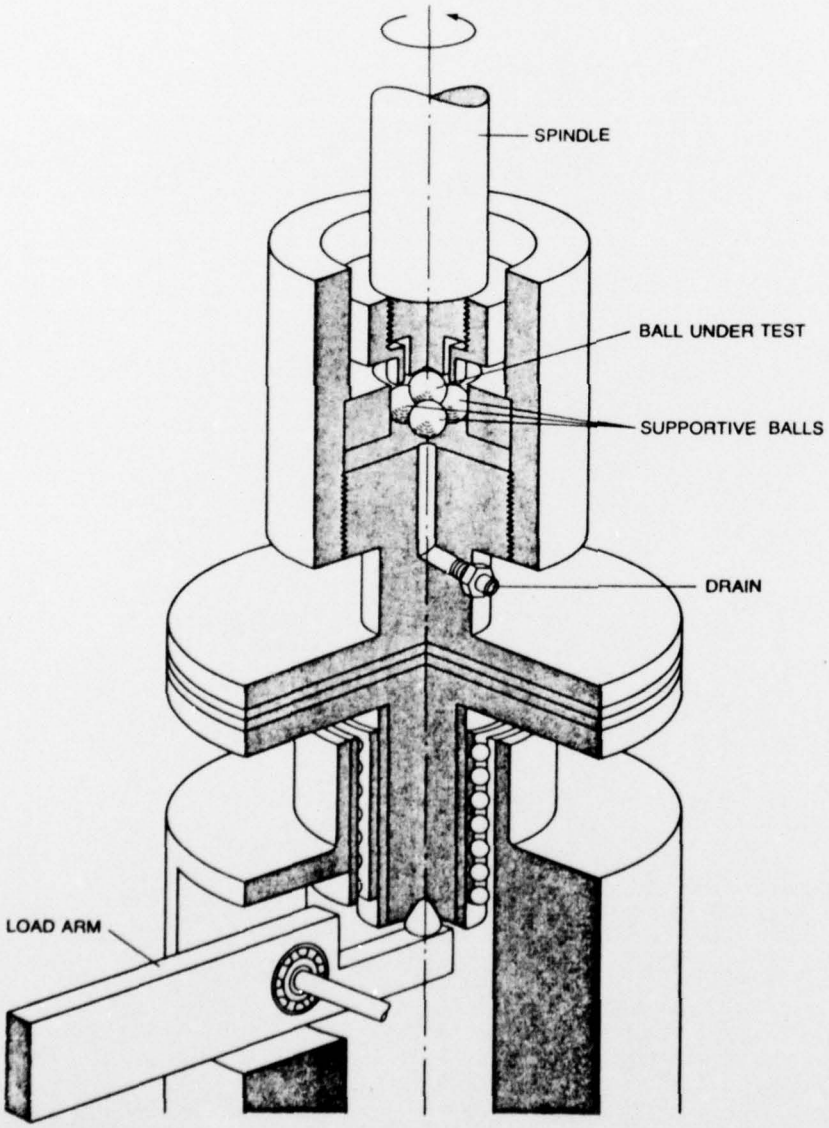
Basically the problem was that if exoelectrons were to be used to obtain knowledge about some other phenomenon, it was necessary to know under precisely what conditions exoelectrons are produced. As we have seen, how-



GROWTH OF CRACKS in an aluminum test strip is revealed in an exoelectron-emission study made by William J. Baxter of the Research Laboratories of the General Motors Corporation. The strip was stressed by repeated bending in a vacuum. At intervals exoelectron emission was stimulated by directing ultraviolet radiation at the surface. Traces show increase in emission after 1,000 and 4,000 stress cycles. The sample failed at location of peak *A* after 140,000 cycles. This showed that exoelectrons can reveal the site of growing cracks.

ever, this is exactly what has proved to be so difficult. Interest in exoelectrons reached a peak in 1957, the year of an international conference on the subject, and then, mainly for lack of progress in explaining the mechanism of their emission, declined to a low point in the mid-1960's. Starting in the late 1960's, however, interest again quickened with the discovery of potential new uses of exoelectrons, some of which I shall now describe.

One of the newer uses exploits the emission of exoelectrons as an index of radiation damage or radiation exposure. It has been found that if certain inorganic materials, such as calcium sulfate, lithium fluoride and beryllium oxide, are exposed to nuclear radiation or other types of high-energy radiation, their crystal structure is damaged in proportion to the length of the exposure. The damage can subsequently be reversed by annealing the material at a specific temperature, usually about 1,000 degrees Celsius. Simultaneously exoelectrons are emitted in rough proportion to the amount of radiation the specimen absorbed. The phenomenon is being considered for possible application in a reusable device for monitoring the radiation exposure of workers in nuclear power plants and similar places. The method promises certain advantages over other monitoring techniques, which measure the leakage of electrostatic charge or the exposure of photographic film.



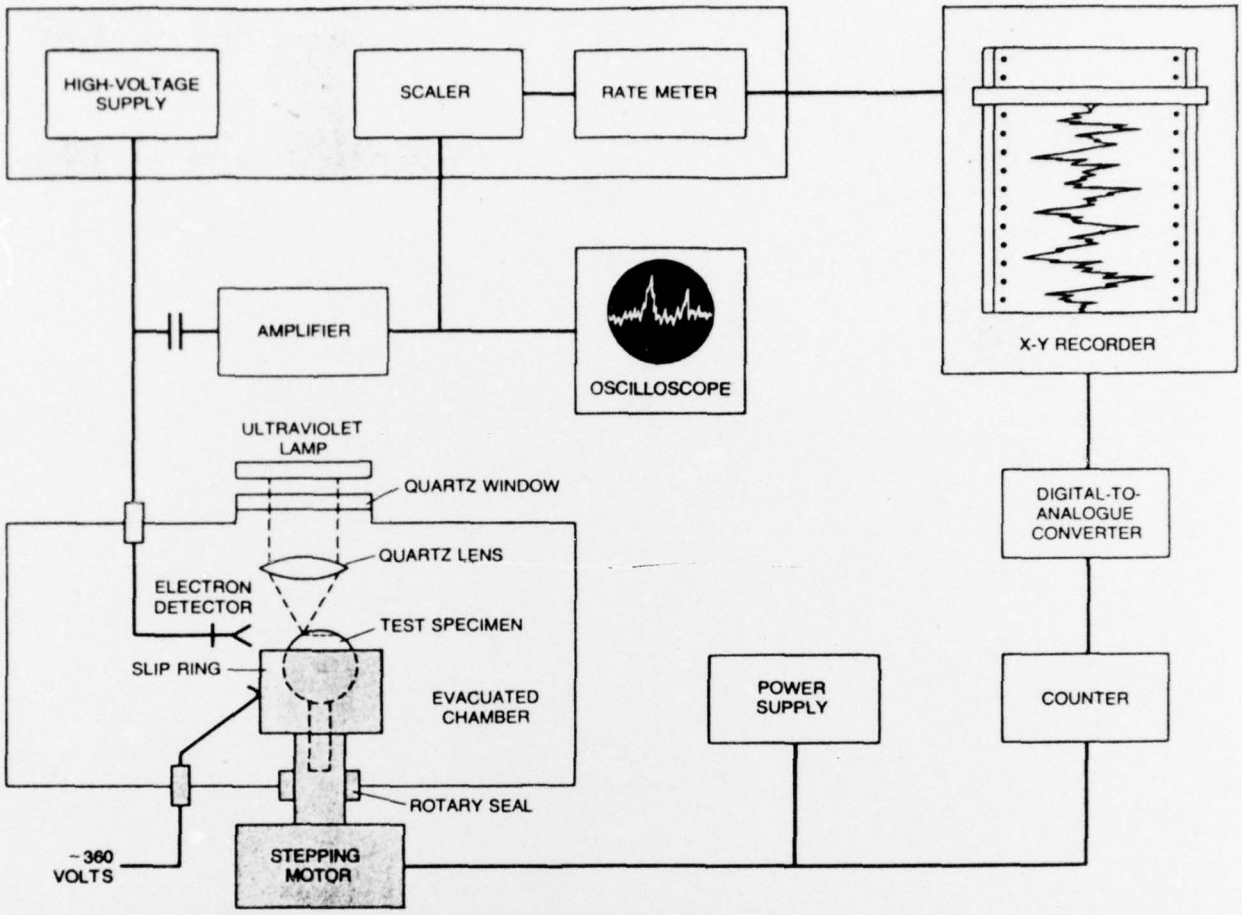
BEARING-BALL FATIGUE is studied with a device in which a test ball, riding on three lower balls, is rotated at 3,560 revolutions per minute. The balls are continuously bathed with fresh lubricant. Contact is confined to a narrow track on the upper ball. The amount of stress on the test ball is governed by the weight on the load arm. The test is stopped when a microphone detects a level of vibration signifying that a ball has developed a serious surface defect.

Another recent use of exoelectrons is for studying the process of crack growth in solids, particularly in the course of fatigue. Fatigue is a mode of failure in metallic solids that are placed under cyclically varying stress. Suppose a metal rod is repeatedly stretched and compressed. If the stresses are less than the yield strength of the metal, it will survive the first applications of stress without suffering damage. If the applications of the alternating stresses are continued, however, the rod will eventually break as the result of fatigue.

Earlier studies had shown that in such cases tiny cracks form in the metal, and that they gradually grow during the successive cycles of stress until the specimen breaks in two. In the early stages of fatigue not only are the cracks usually small and not easy to detect but also at that time there was no way to predict which ones would grow and which ones would remain as they were. Thus the study of crack growth had long presented a difficult problem. Since a growing crack constitutes a freshly exposed surface, however, one would expect it to emit exoelectrons, and it does. As a result exoelectrons are now being exploited to study crack formation and crack growth.

In such studies one should like to be able to locate precisely where the exoelectrons are being emitted. One method of location is purely mechanical. A mask with a small hole is moved slowly across the surface of the specimen in a scanning pattern so that one can tell at each instant the source of exoelectrons reaching the detector. As it happens, a much more elegant technique was available, as a result of earlier work with exoelectrons. One of the diagnostic techniques used by early workers to investigate the exoelectron process was to apply various types of energy (heat, light, mechanical vibration) to surfaces giving off exoelectrons and study the consequences. In general it was found that if external energy is applied, the number of electrons is increased. Electrons released in this way are called stimulated exoelectrons. The most effective stimulator is ultraviolet radiation. The frequency of the radiation must be kept low enough so that the energy in each photon is less than the work function, otherwise photoelectric emission will occur as well as exoelectron emission.

With ultraviolet radiation the number of exoelectrons emitted from a surface can be increased by a factor of more than 10,000 over the normal emission rate. This means that if one small region of a surface is illuminated while the



EXOELECTRON EMISSION from bearing balls was measured and recorded with this apparatus in the author's laboratory at the Massachusetts Institute of Technology. After being removed from the device shown on the opposite page balls are cleaned and mounted in a vacuum chamber so that a narrow beam of ultraviolet radiation will fall on the track of principal wear as the ball is slowly rotated. The beam stimulates the emission of exoelectrons. The exoelectron-emission rate is displayed on oscilloscope and plotted on an *x-y* recorder.

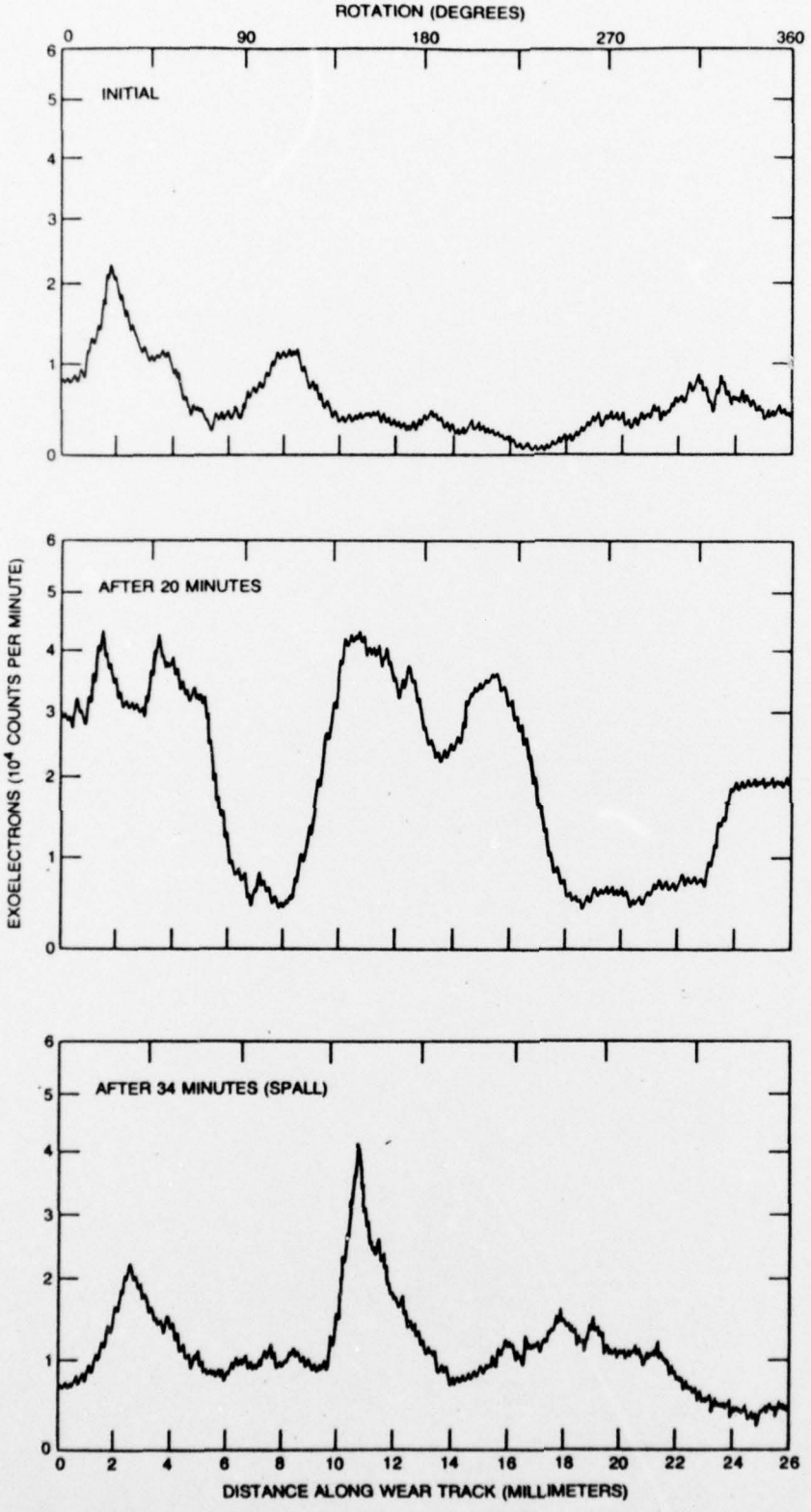
exoelectron emission from the entire surface is measured, nearly all the emission will be generated in the illuminated area. As a result one can sweep a beam of ultraviolet radiation over the surface and simply measure the electron emission as a function of time. The exoelectron count at different times indicates the emission from different areas of the solid surface.

An early demonstration of the information that can be obtained with this technique was published by William J. Baxter of the Research Laboratories of the General Motors Corporation. He placed an aluminum strip in a vacuum chamber containing an electron detector and stressed the strip cyclically by bending it. Simultaneously he slowly scanned the surface with a sharply focused beam of ultraviolet radiation. Before the mechanical stresses were applied there was no exoelectron emission from the surface. After 1,000 cycles three sites gave above-average emission. After 4,000 cycles the active sites had become much more prominent. One of them eventually led to a failure after 140,000 stress cycles. It is clear that the active sites indicate locations where cracks form, grow and extend. Baxter's results were exciting because up to that time no methods were available for identifying fine cracks in metal surfaces and watching them grow to failure.

Baxter's work prompted us at the Massachusetts Institute of Technology to try to apply the same techniques to the problem of crack growth in rolling-contact devices, a process generally referred to as surface-fatigue wear. Surface-fatigue wear is the main cause of failure of ball and roller bearings and an important cause of wear in gears and in wheels rolling on rails. In ball bearings surface fatigue develops when a crack forms in one of the balls and slowly grows until eventually a sizable chip spalls off. Once this happens the bearing is quickly destroyed.

Surface-fatigue wear is an awkward phenomenon to analyze because there is a very large statistical scatter in the time required for failure to occur. Thus if 100 identical ball bearings are tested to failure, the times measured between the first and the last failure may differ by a factor of 100 or more. The problem is made all the more difficult because on a macroscopic scale there are no useful measurements one can make while waiting for a ball to fail. On a microscopic scale one can examine the surfaces for crack formation, but the growing cracks are tiny and hard to locate. At high magnification, to be sure, many fine cracks are visible, but there is no ready way to tell which one is growing rapidly and will eventually lead to a failure. It therefore seemed to us that exoelectrons might provide a way of identifying significant cracks and watching them grow.

The experimental problems seemed considerable. Since exoelectrons travel only very small distances in air before they are stopped, it is virtually essential to conduct experiments with them in a vacuum system. On the other hand, to be meaningful ball-bearing tests must be carried out under the conditions in



HISTORY OF BEARING-BALL FAILURE can be reconstructed by observing the rate of emission of exoelectrons and their location at intervals during a fatigue test. These records were made with the apparatus illustrated on the preceding page. The top trace shows the emission of exoelectrons before the test began. The middle trace shows the emission rate along the wear track after 20 minutes of testing. The ball finally failed by spalling, or losing a flake of material, after 34 minutes. The sharp peak in third trace coincides with location of the spall.

which the bearing usually works: in air with lubricated surfaces. Hence to measure bearing balls for exoelectron emission would call for running tests in a bearing tester in the presence of oil, cleaning off the oil with a solvent, evaporating off the solvent, putting the ball in a vacuum chamber, pumping the chamber down and hoping that all this would not interfere with exoelectron emission. When my colleagues were informed about the experiment, many of them thought it was highly unlikely that after all these manipulations any exoelectrons could be detected, but we decided to go ahead anyway. The U.S. Army Research Office offered to sponsor the work.

Two pieces of apparatus were used, a fatigue tester in which the bearing balls were stressed and a vacuum chamber in which the exoelectrons were to be detected. The fatigue tester was of the Barwell four-ball type, in which a test ball, held by a spindle and rotated at 3,560 revolutions per minute, rides on three lower balls that are constrained by a ring and disk to travel in a circular track. All the balls are half an inch in diameter. (It has been established that tests run in this apparatus, with four balls rolling together, give results that agree well with behavior in a conventional ball bearing, which has an inner race, an outer race and a large number of balls between them.) Lubricant is dripped continuously into the test section. A microphone attached to the four-ball tester measures vibration and automatically shuts off the power when any one of the balls begins to spall. The geometry is such that contact is confined to a relatively narrow track on the upper ball, so that damage and failure generally occur there. Thus only the upper ball need be examined for exoelectron emission.

The evacuated exoelectron-detection apparatus uses ultraviolet radiation for the stimulation of exoelectron emission. The ultraviolet rays pass through a quartz window and are focused on the test specimen with a quartz lens. For the results reported here the spot size was two millimeters by .27 millimeter. The emitted electrons are detected in an electron multiplier. The output pulses are summed and displayed on the y axis of an x-y recorder.

The initial measurements were made of the exoelectron emission from lubricated bearing balls that had been scratched with a diamond scriber and cleaned with a Freon degreaser. The exoelectron-detection apparatus worked as we had hoped, revealing sharp emission peaks when the ultraviolet beam illuminated the scratched region on the ball. We then carried out a number of actual wear tests. In one typical test steel balls were run in the Barwell tester at a

stress level where the anticipated life was about 40 minutes. Every 10 minutes or so the top ball was removed, tested for exoelectron emission and returned to the tester for further stressing. The test ball spalled after a total of 34 minutes of testing. When the wear track on the ball was tested at 20 minutes, it had shown three big peaks of exoelectron emission. The site of one of the peaks proved to be the eventual spall site.

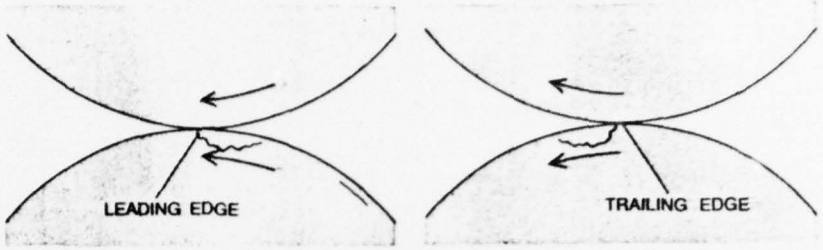
Besides enabling us to locate the position of an eventual surface-fatigue failure, exoelectrons throw light on the mechanism of the failure process. For example, if a bearing ball is stressed in a test apparatus (or in actual use) so that the ball always rolls against the adjacent surface in the same direction, a crack that develops at the surface typically grows inward at an angle and can eventually lead to a spall. The question arises: Does the crack grow in the direction of rolling or away from it? The question can be studied by observing how the exoelectron emission near a crack that grows into a spall varies with time.

Our studies have shown that the leading edge of the eventual spall shows a prominent peak early in the test but that the peak gradually decays, presumably as the crack extends under the surface and parallel to it. The trailing edge shows hardly any exoelectron emission above the background rate until spalling takes place. Hence the crack develops from the leading edge to the trailing edge, confirming earlier studies that had provided less direct evidence.

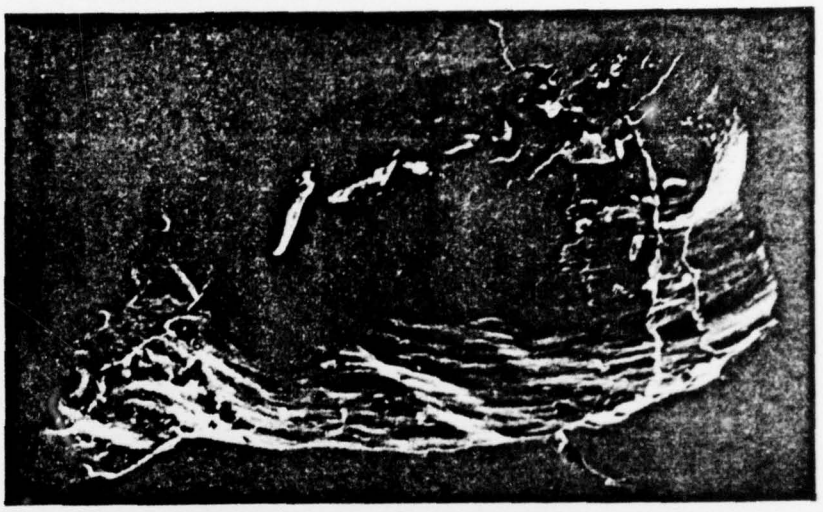
In our work with bearing balls the ultraviolet beam can be directed along a single track because of the way stress is localized in the Barwell tester. One can readily imagine, however, a technique in which the surface of a specimen is swept with a fine ultraviolet beam in a raster pattern while the exoelectron emission is displayed synchronously as the vertical deflection of an electron beam scanning the face of a cathode-ray tube. The first demonstration of such a technique was made in 1969 by C. C. Veerman of the Delft University of Technology in the Netherlands. In his exoelectron images a fatigue crack in an aluminum specimen resembles a mountain ridge [*see illustration on page 75*].

In a similar scanning method the electron-emission rate is made to modulate the intensity of the electron beam in the manner of a television image. In such a picture light areas correspond to regions emitting exoelectrons.

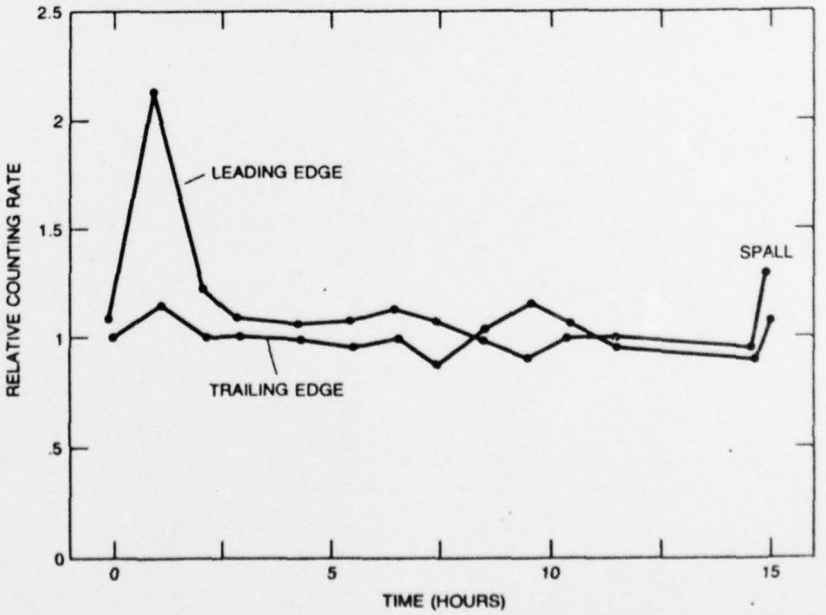
It is risky to predict where future developments of exoelectron-emission phenomena will lead. Within the next decade it should be possible, with special techniques for detecting exoelectrons in air, to make routine examinations of the entire wing structure of an airplane, searching for growing fatigue



CRACK LEADING TO SPALL in a bearing ball might grow from the leading edge to the trailing edge (*left*) or in the opposite direction (*right*). Before development of exoelectron-emission technique there were only indirect methods for establishing the direction of crack growth.

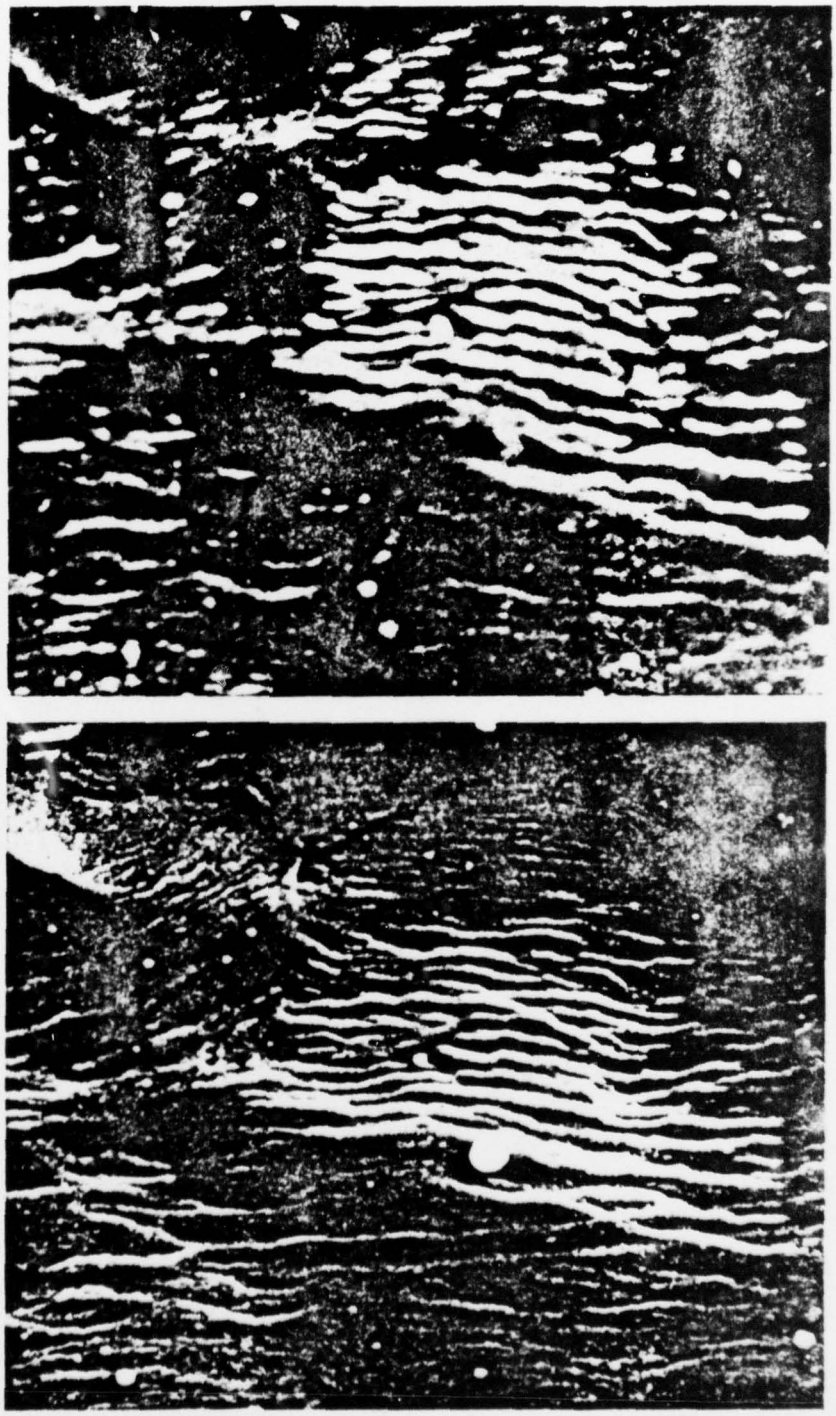


TYPICAL FATIGUE SPALL in a bearing ball is shown in a scanning electron micrograph that was made by the author. The spall is 1.8 millimeters long; the leading edge is at the left.



EXOELECTRON EMISSION from the ball that ultimately developed the spall shown in the micrograph above this illustration enabled the author to establish that the initial fatigue crack appeared at what was to become the leading edge. Exoelectron emission from the leading edge is in color; emission from the trailing edge is in black. Evidently crack starts early at leading edge, then runs under surface, where it cannot be detected, and finally emerges at trailing edge.

cracks. As the speeds of passenger trains increase it will be important to develop fast and reliable methods for detecting incipient flaws in wheels and rails; perhaps exoelectron techniques will serve the purpose. It is conceivable that exoelectrons could be applied in earthquake prediction by indicating which cracks in the surface of the earth or in subsurface rock structures are actively growing. I suspect that as we learn more about the exact conditions underlying the emission of exoelectrons, uses will be found that we cannot imagine today.



TWO TECHNIQUES FOR VISUALIZING CRACKS in a steel surface that had been subjected to plastic strain are compared. The image at the top is an exoelectron micrograph in which brightness is proportional to the emission of exoelectrons. The image at the bottom depicts the same region in a conventional scanning electron micrograph; surface cracks show up as bright lines. The pattern of exoelectron emission closely follows the pattern of cracks. Micrographs were made by Baxter and Stanley R. Rouse of General Motors Research Laboratories.